Mercury Marine Product Development and Engineering

Marine Outboard Catalyst Research Project

Final Report: Large Outboard Catalyst Endurance and Small Outboard Catalyst Design and Development

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Executive Summary

Objective:

The primary goal of the program was to generate an understanding of the exhaust emission reduction potential, engine performance, and engine/emissions systems durability on several marine outboard engine families that included catalytic converters to reduce exhaust emissions. The project was co-funded by the California Air Resources Board (CARB) and was divided into two parts. The objective of the first part was to construct and endurance test two large outboard engines of the same design that were developed under a previous project[1] (CARB ICAT Grant #06-01). The second phase of the project was aimed at investigating exhaust emissions reduction potential using catalysts in the small, four-stroke outboard marine engine segment. Full useful life testing was conducted on the large outboards and the three families of small outboards to understand the emissions deterioration. This program was conducted to serve as a guide for future exhaust emissions standards pertaining to outboard marine engines in the state of California.

Summary of Results:

Overall, the program goals were met. The two large outboard engines equipped with closed-loop fuel control completed the endurance test and maintained HC+NOx levels below the 5.0 g/kw-hr target. Three small engine families were redesigned to incorporate exhaust catalysts. Prototype engines of the three families were constructed and successfully tested. Testing on the small engines included the same endurance test cycle conducted on the large outboard engines. Emissions reductions commensurate with expectations for open-loop fuel systems were observed on the small engines.

As mentioned above, the first portion of the project included the large outboard endurance testing. Two new prototype engines were constructed according to the specifications developed in the original project. The post-endurance emissions results showed the HC+NOx emissions levels were 2.5 g/kw-hr and 3.2 g/kw-hr HC+NOx for the total five mode test. The CO results were within expectations. The total five mode CO emissions were approximately 100 g/kw-hr for both engines, which exceeded the current sterndrive/inboard limit of 75 g/kw-hr. Both engines maintained CO levels for the totals of Modes 2-5 below the alternative sterndrive/inboard limit of 25 g/kw-hr for engines larger than 6.0L displacement. Despite the overall success of the test program, several issues were encountered during testing that would need further refinement to develop a production-ready solution (there is high confidence that a production-feasible design is achievable). Though improvements were made to the catalyst over the original design, the ceramic element slid out of the mantle during the first 60 hours of endurance (15% of the required endurance time). The catalysts were reconstructed with a more robust construction but substrate movement was discovered again after running the final emissions test. Even though the catalyst had slid out of the mantle, there was little damage to the element itself so the emissions results from this engine should still be considered valid. This engine had also failed a pre-catalyst oxygen sensor due to vibration.

The small outboard work started by selecting three engine families less than 50HP and measuring performance, emissions, and water intrusion characteristics of the production, non-catalyst engines. These measurements were used as inputs in the design process. The engine sizes selected were a single cylinder, carbureted 6HP engine; a two cylinder, carbureted 20HP engine; and a three cylinder, fuel injected 40HP engine. The first step of the design process was to select the catalyst type and size. Since the small engines were intended to be open-loop fueling system engines, the catalysts were sized larger than the catalysts used for the large outboard testing, on a specific basis relative to the exhaust flow. Both ceramic and metallic catalyst elements were used. The small outboards were designed to simulate the limitations of the processes that would likely be used to construct production engines. As expected, the weights of the catalyzed outboards increased relative to the current non-catalyst engines. The weight increase measured on one of the engine families caused the total weight to exceed the threshold of what Mercury would consider a portable engine, a key product requirement for that engine family.

Once built, the engines were tested on the dynamometer to evaluate the mechanical systems to make sure the design was sound. Several changes were made to the 20HP and 40HP prototype engines' cooling systems to optimize the performance of the systems. The fuel systems were also calibrated to deliver the best balance of emissions performance, hardware durability, and running quality. During the calibration effort, the influence of air/fuel ratio on emissions was quantified. Using the emissions trends as a function of air/fuel ratio in combination with air/fuel ratio variability of the fuel systems on current production, non-catalyst engines, the total post-catalyst emissions variation was quantified. The analysis showed there would be catalyst engines that would produce higher HC+NOx emissions than the lowest emitting non-catalyst engines. However, the average emissions output from an engine family would be expected to be reduced from the current, non-catalyst level.

The endurance testing of the small outboard engines included tank testing and boat testing. The tank test consisted of 100 hours of full power operation and was performed to verify the integrity of the prototype hardware prior to the boat endurance test. The boat endurance test was run as a cycle to mimic the International Council of Marine Industry Associations (ICOMIA) duty cycle[2] and was intended to simulate customer usage. The boat test was conducted for 350 hours of endurance time. Emissions tests were conducted at the start, middle, and end of the endurance test to quantify the emissions deterioration. Overall, the endurance testing on the small engines was very successful as no hardware issues were encountered with the prototype parts or catalyst exhaust systems on any of the engines. The results of the emissions tests were heavily influenced by the air/fuel ratio variability, making it difficult to separate the effects of engine-out emissions changes versus catalyst deterioration effects. The final emissions outputs of the three small engine families are shown in the table below.

Table 1: Small Outboard Post-Boat Endurance Emissions Results

	HC+NOx [g/kw-hr]			CO [g/kw-hr]		
Engine	Start	Finish	% Increase	Start	Finish	% Increase
6HP	7.1	11.1	56.3	118	144	22.0
20HP	5.8	4.7	-19.0	108	125	15.7
40HP	4.3	4.8	11.6	68	90	32.4

Conclusions and Recommendations:

Large Outboard Endurance:

- The large outboard engines (using closed-loop fuel control at most emission mode points) were able to meet the 5.0 g/kw-hr HC+NOx target, similar to the catalyst sterndrive/inboard limit.

- The CO emissions of the large outboards were in-line with expectations, but did not maintain levels below the current 75 g/kw-hr standard imposed on the catalyzed sterndrive/inboard engines. However, the engines were shown to meet a 25 g/kw-hr standard when considering only Modes 2-5 (alternate standard for sterndrive/inboard engines larger than 6.0L).

- Work is needed to develop a more robust mounting design for the ceramic catalyst element used in the large outboard engines.

Small Outboard Design and Development:

- Catalyst exhaust systems were successfully designed, constructed, and endurance tested on three families of small outboards, which met the goals of the program.
    - The engines tested reduced the amount of HC+NOx emissions output compared with their non-catalyst counterparts.

- Air/fuel ratio control was the most critical factor in the post-catalyst emissions output.
    - Air/fuel ratio control was a larger factor than the engine degradation or catalyst deterioration.
    - The amount of air/fuel ratio variability determined in this study was based on current production emissions audits and should be representative of engines industry-wide.
    - Since the CO conversion efficiency dropped to near zero in rich operation with the catalyst system, it was expected that under the worst-case conditions the post-catalyst CO emissions would essentially equal the engine-out CO emissions.

Large Outboard Endurance Testing

Introduction

In order to better understand how catalyzed outboard engines perform over the full useful life of the product, endurance testing was conducted. Mercury previously performed a project funded by CARB ICAT Grant #06-01 that evaluated the implementation of catalysts on two spark-ignited, four-stroke outboard engine families. The project successfully developed four running prototypes of a 200 hp outboard engine equipped with a three-way catalytic converter. These engines reduced the HC+NOx emissions by 88 percent and had deteriorated emissions that were estimated to be below the CARB 4-star limit of 5 g/kw-hr HC+NOx.[1] However, the endurance test engine in the original study was only tested to 100 hours of endurance time so the deterioration factor was not determined definitively.

The goal of this project as defined in the contract was to run an additional two engines of the same design as the original project for 350 hours of saltwater boat endurance to determine the full useful life deterioration of the catalyst system.

Preparatory Work: Engine Build

Two new, prototype test engines were constructed to complete testing. In order to accomplish this, two new, production (non-catalyst) engines were obtained (random selection) from the stock of engines in the warehouse. The test engines were built with prototype castings for the cylinder head, cylinder block, and exhaust system components. The exhaust manifolds were cast using an updated gating system in the casting process and were not from the same batch of components used in the original project. In addition, the adapter plates were modified to accommodate the unique catalyst exhaust system. Other small prototype components were fabricated and stock components were modified accordingly to complete the rest of the engine build to match the design/construction of the engines from the original project.

Preparatory Work: Catalyst Construction

During the testing portion of the original project (both dynamometer testing and boat endurance testing), the ceramic elements of several catalysts were found to have slid out of the metallic mantle. A damaged catalyst was sent to the supplier of the matting material for analysis. After analyzing the catalyst, engineers at the supplier concluded that the matting material used was not providing enough clamping pressure on the catalyst. The recommendation was to use a higher density matting to avoid further issues. See the report from the original project for complete details.[1]

Following the suggestions made in the supplier's report, the prototype catalysts were constructed in a slightly different manner than those used in the original project. The matting material was the same, but the density was increased to provide additional clamping pressure on the ceramic element. The remainder of the design of the catalyst was the same as used in the original project. The new catalysts were built using the same size ceramic substrate with the same precious metal loading and an appropriately-sized, stainless steel mantle with the necessary mounting flange on the mantle.

Saltwater Boat Endurance Test Procedure and Test Sequence Description

Once the prototype engines were constructed and all preparatory work was completed, the emissions deterioration testing process began by preparing each engine. This included instrumentation of the test engines as well as performing some basic checks. The instrumentation process included installation of an exhaust emissions probe that met the requirements of the EPA 40 CFR Part 91 regulations[3].

Each engine was rigged onto an appropriate dynamometer and a break-in process was performed. The break-in consisted of increasing speed and load settings and was performed on non-ethanol (E0) gasoline for all engines. This was followed by a power run to determine the wide open throttle (WOT) performance of each engine. The power run included speed points from 2000RPM up to the maximum rated speed of the engine.

Once the WOT performance was checked, emissions testing was performed using reference-grade E0 gasoline (EEE fuel: EPA Tier II emissions reference grade fuel). The emissions tests were run in accordance with the EPA requirements set forth in 40 CFR Part 91. A summary of the emissions mode points are shown in Table 2 below. Two emissions tests were run at each endurance interval (i.e. before endurance, at the midpoint of endurance testing, and after endurance testing). One emissions test was conducted with emissions probes installed before and after the catalyst to allow catalyst conversion efficiency calculations. The other emissions test was done with the post-catalyst measurement only. The post-catalyst only emissions tests were used as the "official" emissions tests to calculate the deterioration factor since this would be the standard practice for certification or audit measurements.

Table 2: Emissions Mode Point Description[3]

Mode Point	Engine speed as a percentage of engine rated speed	Engine torque as a percentage of maximum torque at rated speed	Mode weighting factor
1	100	100	0.06
2	80	71.6	0.14
3	60	46.5	0.15
4	40	25	0.25
5	idle	0	0.40

Following the above emissions checks, each engine was prepared for endurance testing. This included doing a basic visual inspection as well as some general engine power cylinder integrity checks (example: compression test and cylinder leak-down). These integrity checks were also repeated at the endurance midpoint and endpoint.

The first half of the endurance test was then performed. The engines were shipped to Mercury's saltwater boat endurance test facility. The engines were rigged as a dual application on a 30' vessel, as shown in Figures 1 and 2 below. Each engine was fitted with the appropriate propeller to operate the engine approximately in the midpoint of the rated speed range at wide open throttle. The fuel used for endurance testing was gasoline with 10% ethanol (E10). The engine instrumentation was continuously monitored and data were recorded for the duration of the endurance test. Periodic scheduled maintenance was performed on each engine per the Owner's Manual appropriate for the non-catalyst equivalent engine. This maintenance was performed in typical customer maintenance intervals since the boat endurance test procedure was intended to simulate typical customer use. The engines were operated at approximate speed points for given durations to simulate the ICOMIA test cycle[2]. Testing included shifting, shutdown, and startup maneuvers to simulate real world usage. Testing on the boat in the saltwater environment provided a variety of environmental conditions and various sea conditions.

Figure 1: Large Outboard Boat Endurance Installation – Front/Top View

Figure 2: Large Outboard Boat Endurance Installation – Side/Back View

Once the first half of the endurance testing was completed, each engine was rigged on the dynamometer again. Emissions tests on the appropriate fuel were performed according to the procedures described above. Each engine also received a visual inspection and the general engine power cylinder integrity checks before being returned to endurance testing.

After the midpoint emissions testing was completed, each engine was returned to the saltwater boat endurance test facility to complete the second half of the endurance testing. The testing was performed in the same manner as the first half of the endurance portion.

When the endurance testing was complete, each engine was returned to the dynamometer for post-endurance emissions tests on the appropriate fuel. A post-endurance WOT performance power run was also conducted to compare with the pre-endurance power run.

Finally, after all running-engine tests were completed, the exhaust systems from each test engine underwent a complete tear-down/disassembly and inspection. This inspection included checks and measurements to assess catalyst integrity, corrosion issues, oxygen sensor condition, etc. The engine also received the general engine power cylinder measurements to ensure integrity.

Problems Encountered during Testing

Catalyst Mounting Failure

During a routine inspection at 53 hours of boat endurance testing (15% of the endurance test time), the catalyst in one of the test engines was found to have moved from its intended mounting location. The ceramic element of the catalyst was found to have partially slid out of the mantle of the catalyst. Please see the photograph in Figure 3 below for details.

As noted in the “Catalyst Construction” section above, the same issue was found in the original outboard marine catalyst testing project[1]. When the catalysts were built for this test, the catalysts were constructed with a higher density mount mat to increase the holding pressure applied to the ceramic element based on the supplier’s recommendations.

Figure 3: Catalyst Mounting Failure: Ceramic Element Extending Out from the Mantle

Since increasing the holding pressure by increasing the density of the mount mat did not solve the problem, a more significant modification was necessary to correct the problem in order to complete the testing. The catalyst with the mounting issue, the catalyst from the other boat endurance engine that did not have an issue, and two new, spare catalysts were sent to the catalyst supplier for modification. The catalysts were modified with a stop ring on the bottom edge to form a positive stop. The stop ring was essentially a washer welded to the end of the mantle. A piece of wire mesh was installed as a cushion between the ceramic element and the stop ring to prevent damage to the ceramic. See Figure 4 below. Due to the damage caused to the outside edge of the outlet face on the catalyst, the ceramic element was inverted end-for-end (the damaged outlet face became the inlet face) to allow proper seating of the ceramic element against the wire mesh/stop ring. Please see Figure 4 below showing the details of the repair method. Though there were some applications identified as a precedent for vertically mounted ceramic catalysts with stop rings, it was not known how this assembly would perform in the outboard marine application.

Figure 4: Catalyst Repaired/Modified to Include Stop Ring

There were concerns about the emissions reduction ability of the damaged catalyst that needed to be addressed due to the repair method. Because the ceramic element was inverted end-for-end, it could have affected the deterioration characteristics. The small amount of material removed from the catalyst could have affected the conversion efficiency of the catalyst. The stop ring covered several of the outside rows of the catalyst, which could have slightly lowered the effectiveness of the catalyst and increased the exhaust back pressure. Emissions tests were conducted on the dynamometer to validate the repair of the ceramic element catalysts. Both endurance catalysts showed approximately the same amount of deterioration when comparing the conversion efficiencies of the baseline emissions tests with the post-repair emissions tests. This indicated that the slight damage on the corner of the catalyst caused when the catalyst contacted the exhaust housing did not appreciably change the effectiveness of the catalyst. This also confirmed that flipping the catalyst end-for-end did not affect the catalyst performance. In addition to testing the repaired endurance catalysts, a new catalyst that received the stop ring modification was also tested to allow comparison with the endurance catalysts when they were new. The new catalyst that received the modifications showed approximately the same conversion efficiency of the endurance catalysts when they were new (prior to the addition of the stop ring). The slight reduction in available cells due to the stop ring coverage did not affect the overall effectiveness of the catalysts when new.

The main effect that was noticed was the increased exhaust back pressure. Figure 5 below shows the difference in back pressure due to the addition of the stop ring. The additional back pressure caused a peak power loss of approximately 3-5HP. The increased exhaust restriction also caused the engine to run rich in the open-loop WOT region due to the reduction in airflow through the engine. The rich air/fuel ratio (AFR) caused a 25% increase in CO emissions at Mode 1 (WOT) and slight changes to HC and NOx.

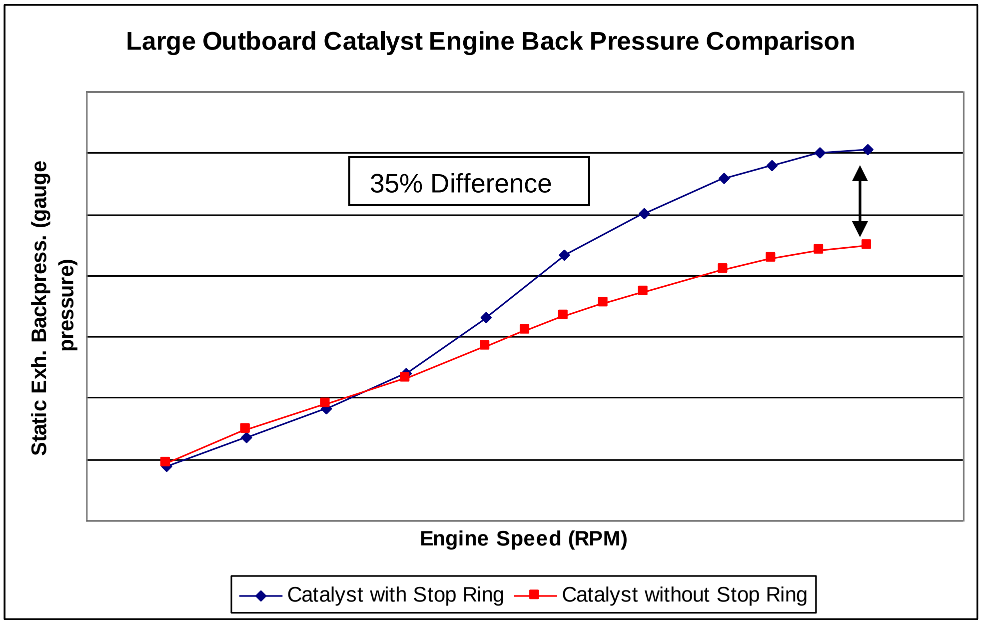


Figure 5: Exhaust Back Pressure Comparison of Catalyst Modification

Due to the changes in power output and air/fuel ratio in open loop, the final calculated emissions output characteristics of the engines changed. Since the emissions were calculated on a specific basis by dividing by the power output, any reduction in power with all other factors held constant would result in a higher calculated specific emissions output. Since the power was shown to be reduced by 2-4%, the final calculated emissions values were 2-4% higher than the baseline values.

The bigger effect from the back pressure difference was caused by the change in air/fuel ratio at Mode 1 due to the lower airflow through the engine (wide open throttle, open-loop operation). As a result, when the endurance engines were emissions tested at the midpoint and endpoint of the endurance interval, the Mode 1 emissions data were collected with the as-calibrated, resulting air/fuel ratio and then with the air/fuel ratio adjusted to match the baseline air/fuel ratio from the original emissions test. In this way, the sensitivity to air/fuel ratio was understood and it was possible to correct the data to account for the error caused by the change in back pressure. However, this approach masked any actual fuel system drift or variability that would normally be experienced during the endurance test for the open-loop Mode 1 operation.

After the stop ring modifications/repairs were validated, the repaired catalysts were reinstalled in the boat endurance engines and the rest of the endurance testing was completed. Once all the endurance testing and dynamometer emissions tests were complete, the engines had the exhaust systems removed for inspection. The end of test inspection of the exhaust systems revealed the catalyst had once again slid out of the mantle. This time, however, the catalyst pushed on the stop ring, which was installed to prevent this failure mode, and broke two of the welds. The catalyst was eventually retained due to stop ring straddling the catalyst with the two remaining welds. The catalyst suffered minor damage due to hard contact with stop ring. Figure 6 shows the condition of the catalyst during the time of the final emissions testing on this engine.

Figure 6: Catalyst after Endurance with Failed Stop Ring

The failed catalyst was analyzed to determine the cause of the failure. Several issues may have contributed to the failure. These issues would include manufacturing process, mat deterioration, vibration, excessive temperature, and insufficient weld size/strength on the stop ring. In order to determine if changes made to correct all or some of the issues noted, more endurance testing would be necessary but was outside the scope of the project. Root cause was not fully identified at the time this report was written as the suppliers were still conducting additional testing as part of the investigation. Despite lack of fully understanding the root cause of the problem, there is still high confidence that an adequate solution for the catalyst mounting issue could be developed for production or a suitable replacement (metallic substrate) could be implemented. This confidence is partly based on the fact that the other engine used in the study, running under identical operating conditions (dual engine test vessel), did not show any indications of substrate movement.

Pre-Catalyst Oxygen Sensor Failure

It should be noted that the post-endurance emissions test on one of the engines was run with a new oxygen sensor (O2 sensor) installed in the pre-catalyst position. This occurred on the same engine that manifested the catalyst mounting issue. The OBD system set a fault approximately one hour before the end of the endurance test. During the post-endurance dynamometer emissions test, the sensor was shown to be unable to properly measure the exhaust gas. Therefore, the control system was unable to properly control the air/fuel ratio during the emissions test and the sensor had to be replaced since the engine was running lean at certain mode points. When the sensor was replaced, the control system was able to properly adapt the fueling and the diagnostic fault was eliminated.

The failed sensor was inspected for further analysis. The sensor was dissected to check for evidence of water intrusion. Upon dissection, no evidence of water intrusion was noted. However, the ceramic element of the sensor was found to be cracked. It is possible that the ceramic was damaged during the dissection process, but the fact that the engine controller was not adapting properly would indicate some type of malfunction in the sensing element. One of the most logical causes of failing the sensing element would be from excessive vibration. To better understand the vibration levels experienced at the oxygen sensors, a running engine test was performed with 3-axis accelerometers adhered to the oxygen sensors and the manifold adjacent to the oxygen sensors. Data were taken at both the pre-catalyst and post-catalyst oxygen sensor locations. When measured data were compared to the supplier's specification, several areas were identified where the vibration levels of the pre-catalyst oxygen sensor exceeded the specification limits. The values for the post-catalyst sensor did not exceed the limits. This supports the evidence that suggests the ceramic element had failed during service and was not broken during the sensor dissection process.

Emissions Deterioration Testing Results

The main conclusion from this testing was the overall deteriorated HC+NOx emissions were maintained below the target limit of 5 g/kw-hr, which was based on the existing sterndrive/inboard CARB 4-Star limit. The results from the combined 5-mode HC+NOx totals as a function of endurance time can be seen in Figure 7 and Table 3 below. The HC+NOx values increased on both engines with increasing endurance time.

It should be noted that the engine that had more overall deterioration was also the engine that suffered damage to the catalyst as a result of the ceramic element sliding out of the mantle. There was some catalyst element loss as a result of the damage and may have contributed to the higher deterioration. However, the amount of deterioration on the engine with the damaged catalyst was within a reasonable range so the results should still be included in drawing conclusions from the testing. In the figures below, the engine that had the damaged catalyst is referred to as Engine 1.

Note: The NOx results are described as “corrected NOx” because the humidity correction factor was applied to the results, as is the case for all NOx data illustrated in this report.

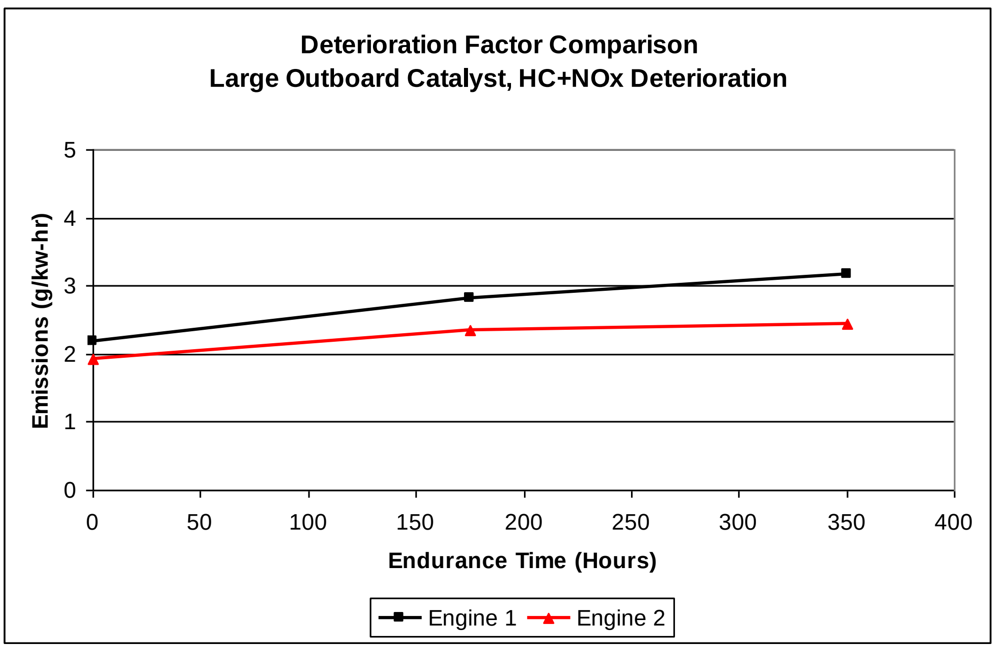


Figure 7: Weighted Specific HC+NOx 5-Mode Totals vs. Endurance Time

Table 3: Summary Table for Large Outboard Endurance HC+NOx Emissions Results

Engine	HC+NOx [g/kw-hr]		
	Start	Finish	% Increase
Engine 1	2.2	3.2	45.2
Engine 2	1.9	2.5	26.9

Figure 8 below shows the weighted specific 5-mode total CO output as a function of endurance time for the endurance engines. The majority of the CO emissions were generated at Mode 1 (WOT operation: rich fueling and open-loop operation) and since the air/fuel ratio was adjusted at Mode 1 to account for the differences caused by the stop ring, the deterioration may be understated. The total CO emissions from Modes 1-5 exceeded the current sterndrive/inboard limit of 75 g/kw-hr. The alternative sterndrive/inboard CO considers the CO emissions from Modes 2-5 only and the limit is set at 25 g/kw-hr for sterndrive/inboard engines larger than 6.0L. The Mode 2-5 CO totals for both engines are shown in Table 4 below. Both engines tested yielded Mode 2-5 CO totals below the 25 g/kw-hr standard.

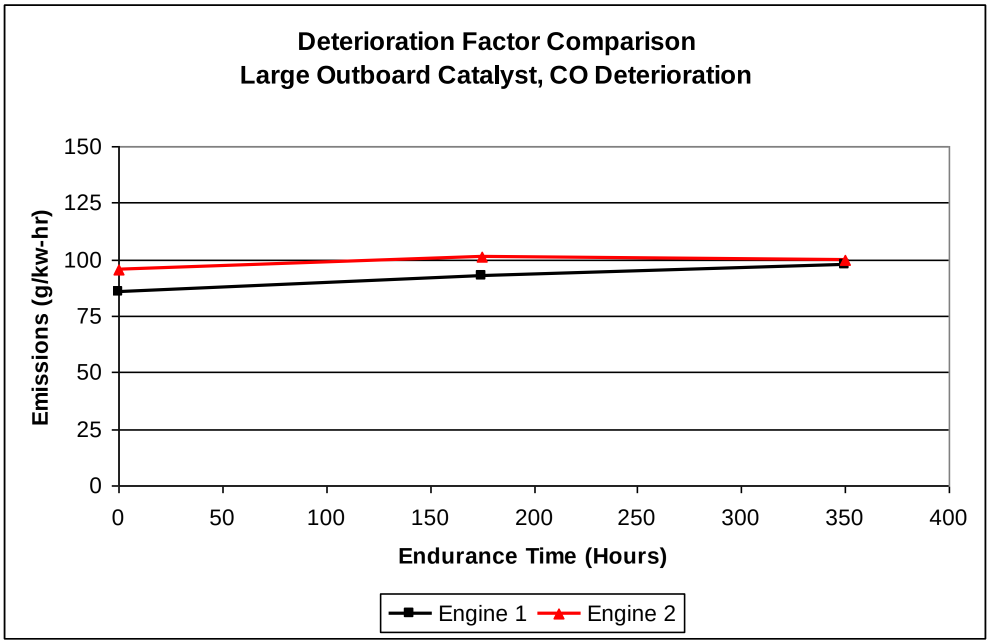


Figure 8: Weighted Specific CO 5-Mode Totals vs. Endurance Time

Table 4: Summary Table for Large Outboard Endurance Emissions Results

Engine	CO Total [g/kw-hr]			CO Mode 2-5 [g/kw-hr]		
	Start	Finish	% Increase	Start	Finish	% Increase
Engine 1	86	98	14.0	4.9	19.7	298
Engine 2	95	100	5.3	5.1	12.6	146

Performance Test Results

In addition to the emissions measurements, the engine torque output was measured. Figures 9 and 10 show the torque and power output as a function of engine speed for each test engine before and after endurance. The peak power output of both engines was lower after endurance. This is due to a combination of normal engine performance deterioration and the fact that the catalysts were modified part way through the test to include the stop ring, which increased exhaust back pressure.

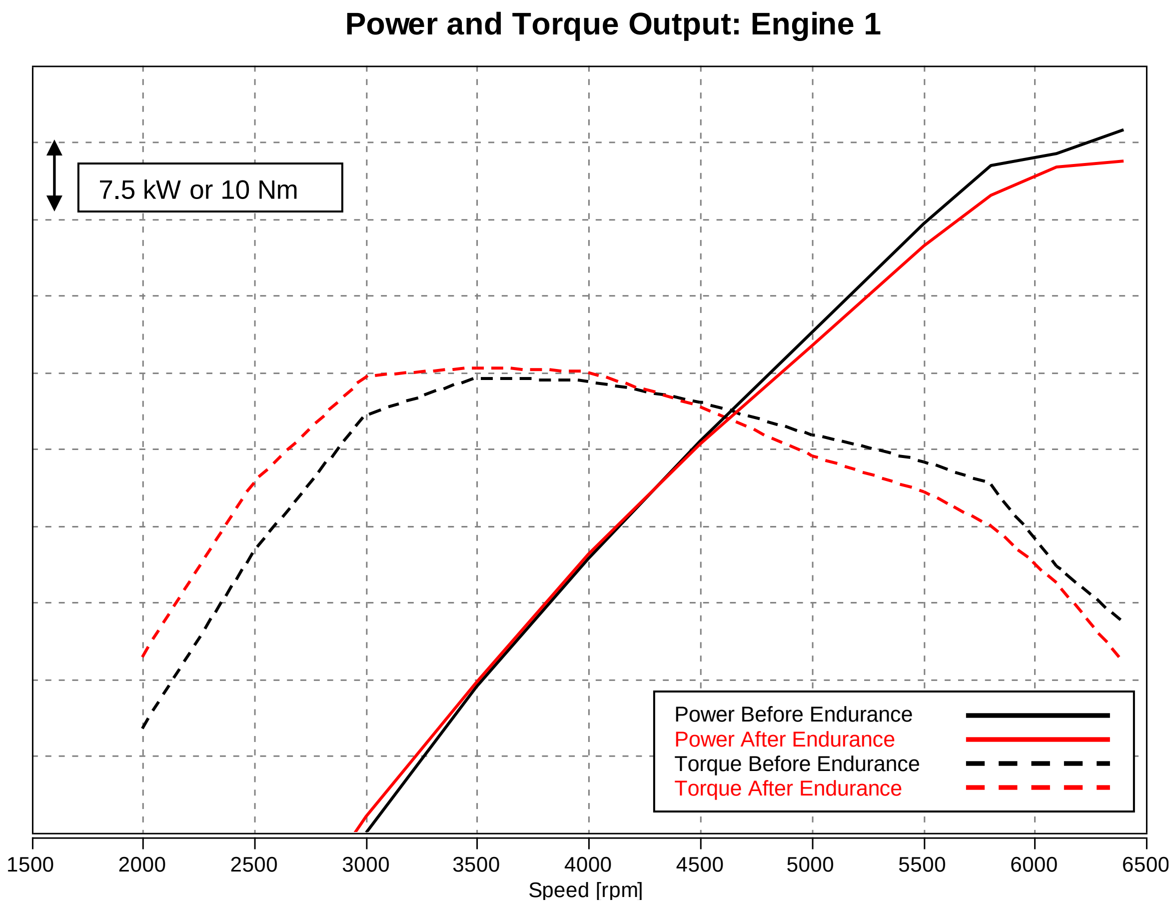


Figure 9: Engine Performance Before and After Endurance, Engine 1

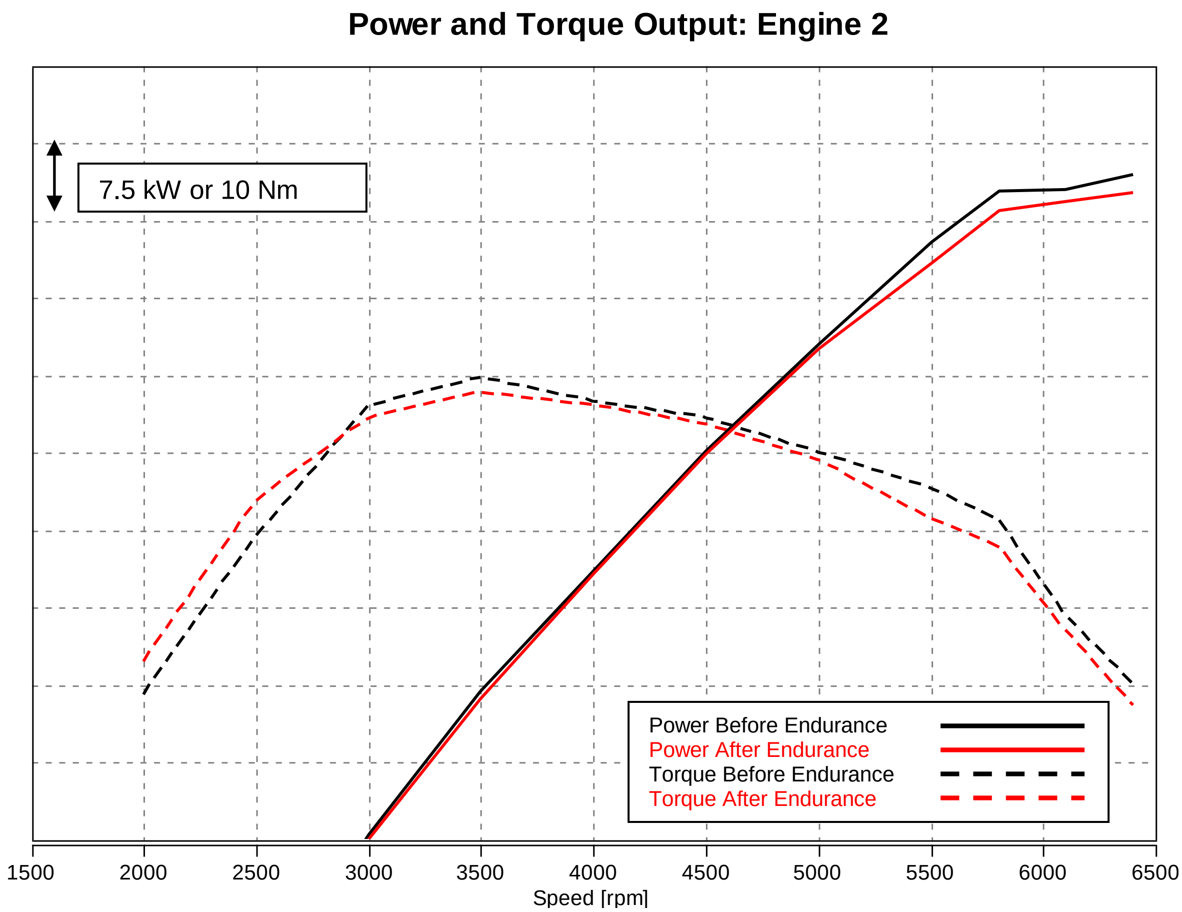


Figure 10: Engine Performance Before and After Endurance, Engine 2

Final Hardware Inspection

Once the boat endurance test was completed, the exhaust systems of both engines were torn down and inspected. During this inspection, the catalyst from engine 1 was found to have slid out of the mantle again despite the stop ring, as discussed in the “Problems Encountered during Testing” section above. Aside from the catalyst mounting failure, the engines and the exhaust systems appeared to be in good condition. There were no indications of water present in the exhaust system either from condensation or from reversion/splash back. See Figure 11 below.

Figure 11: Exhaust Ports from Engine 1 showing No Evidence of Water Contact

Summary of Results and Conclusions – Large Outboard Endurance

Overall, the large outboard endurance testing demonstrated that the engines were able to meet the 5 g/kw-hr HC+NOx target emissions level at the end of the endurance test. The 5 g/kw-hr HC+NOx target was derived from the current sterndrive/inboard standard. The engines ran 2.5 g/kw-hr and 3.2 g/kw-hr HC+NOx for the total five mode test after endurance. The CO emissions were primarily driven by the rich air/fuel ratio at Mode 1 to keep exhaust temperatures under the mechanical limit. The total five mode CO emissions were approximately 100 g/kw-hr for both engines, which exceeded the current sterndrive/inboard limit of 75 g/kw-hr. Both engines maintained CO levels for the totals of Modes 2-5 below the alternative sterndrive/inboard limit of 25 g/kw-hr for engines larger than 6.0L displacement.

While results were encouraging, there were several issues that arose during testing that illustrate more development and refinement would be necessary before a production-feasible design would be ready. The most concerning failure was the catalyst that had the ceramic element slide out of the mantle. Despite efforts to incorporate a solid stop, the catalyst exerted sufficient force to cause the stop ring to fail. Another concerning failure was the pre-catalyst oxygen sensor. The subsequent testing showed that the sensor failed due to elevated vibration levels.

Aside from the catalyst failure mentioned earlier, inspection of the exhaust system hardware showed positive results. There were no signs of water intrusion near any of the oxygen sensors, nor any signs of water condensation in the exhaust ports. However, these engines were not subjected to Mercury’s standard full outboard qualification tests.

Small Outboard Catalyst Development

Introduction

The main focus of this portion of the research project was to determine the emissions reduction potential of small outboards when equipped with catalyst technology appropriately suited for the small outboard market. The charter for the project specified development and testing on three engine families under 50HP and included full emissions deterioration testing based on 350 hours of saltwater boat endurance. Fuel systems were limited to carburetion or open-loop fuel injection in order to develop a solution that would be appropriate for the market.

The small outboard market has unique considerations that drove the necessity for this portion of the project. In general, the small outboards are intended to be simple, rugged designs that are inexpensive to manufacture in order to compete in the global marketplace. Many of these engines are not permanently mounted to a particular boat hull and are intended to be portable engines. As a result, total engine weight and size are very important aspects of the design.

Test Engine Description

Prototype designs from three separate engine families less than 50HP were developed for this research project. In order to develop catalyst systems on a wide range of engines from this segment, one-cylinder, two-cylinder, and three-cylinder engine families were selected. All three engine families were four-stroke engines and had open-loop fueling systems. Table 5 below shows the general specifications for the non-catalyst, production versions of the engine families selected for the study. The specific engines selected represent the highest power output one-cylinder, two-cylinder, and three-cylinder four-stroke outboard engines Mercury offered at the time.

Table 5: Engine Specifications – Small Outboard

Engine Family	6HP	20HP	40HP
Gas Exchange Process	Four-Stroke	Four-Stroke	Four-Stroke
Cylinder Configuration	Single Cylinder	Inline 2 Cylinder	Inline 3 Cylinder
Displacement	123CC	351CC	747CC
Fuel / Induction System	Single Carburetor, 2 Valve per Cylinder, Pushrod	Single Carburetor w/Accelerator Circuit, 2 Valve per Cylinder, Single Overhead Cam	Multi-Port Electronic Fuel Injection (Open-Loop), 2 Valve per Cylinder, Single Overhead Cam
Published Dry Weight of Lightest Model	55 lbs / 25 kg	115 lbs / 52 kg	214 lbs / 97 kg
Images (Not Scaled Relative to the Other Images)			

Boundary Condition Data Collection

Once the engine families were selected, current production, non-catalyzed versions of the engines were tested to gather reference data to provide input into the design process of the catalyst exhaust systems. The inputs were used to determine catalyst design parameters like overall size, cell density, and washcoat formulation. The data also helped develop the cooling system and the overall exhaust system layout. The input consisted of data generated on the dynamometer including baseline exhaust emissions output, power, effects of exhaust back pressure on performance, general exhaust gas temperature/pressure/flow measurements, etc. Tank testing was also performed to determine water intrusion characteristics of the base engines. Water intrusion data were used to help determine proper catalyst placement in the engine. Additional data from previous endurance testing were also analyzed to understand oil consumption trends. High oil consumption would have caused oil poisoning of the catalyst leading to more pronounced emissions deterioration.

Emissions data were collected on the baseline engines, as shown in Figures 12 and 13 below. Figure 12 shows the HC+NOx data for each mode point. Due to the weighting factor and high specific load, Mode 2 tended to generate the largest portion of emissions on all three engine families. Mode 5 emissions (and Mode 4 emissions to a lesser degree) had higher contributions to the total emissions level on the 6HP engine compared with the other engines. This is predominantly a function of elevated hydrocarbon emissions caused by the relatively rich air/fuel ratios required on the 6HP engine to achieve acceptable running quality at low speed. The same trend was also apparent when looking at the CO data in Figure 13. The primary driver for CO emissions was the air/fuel ratio. Rich air/fuel ratios increase CO production, so it is clear from looking at the data in Figure 13 that, in general, the 6HP engine runs the richest air/fuel ratios, followed by the 20HP, with the 40HP engine running leaner. The trend of more fuel rich operation is generally due to inherently higher engine running quality instability of the smaller engines due to lower cylinder count, among other factors.

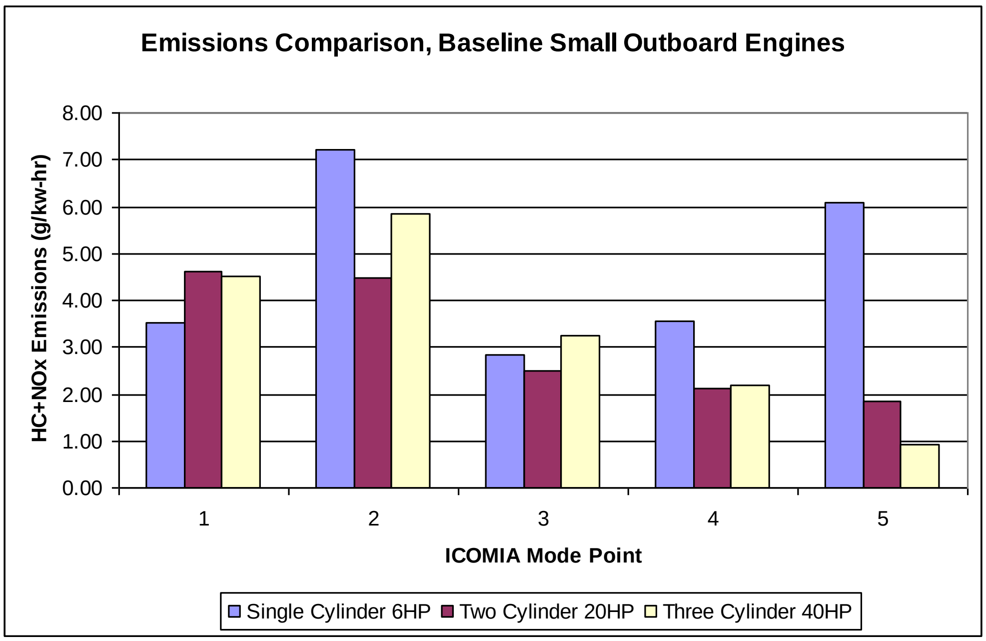


Figure 12: HC+NOx Emissions, Baseline, Non-Catalyst Engines

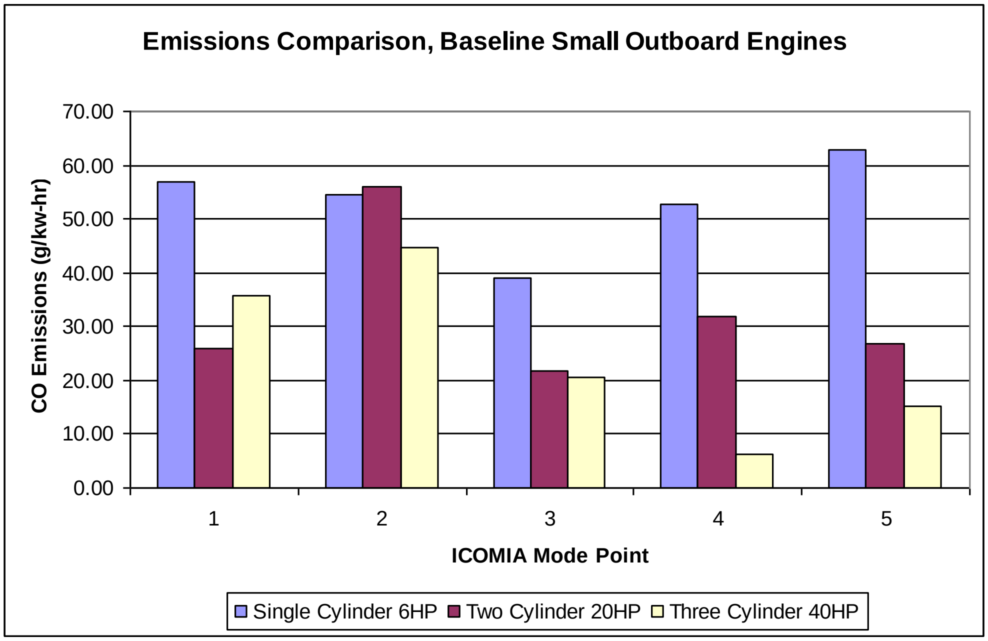


Figure 13: CO Emissions, Baseline, Non-Catalyst Engines

To further break down the baseline emissions test, Table 6 below was created. The table shows the HC and NOx totaled separately to gain understanding. Again, it is evident that the 6HP engine generally ran richer air/fuel ratios and the 40HP engine generally ran leaner air/fuel ratios. For the 6HP engine, of the total HC+NOx value, 78% was HC, as compared with the 40HP engine, where less than 50% of the total was HC.

Table 6: Total Emissions Output Comparison, Baseline, Non-Catalyst Engines

	6HP	**20HP**	**40HP**
HC +NOx Total (g/kw-hr)	23.3	15.5	16.8
HC Total (g/kw-hr)	18.1	8.8	8
NOx Total (g/kw-hr)	5.2	6.7	8.8
HC%	**78%**	**57%**	**48%**
NOx %	**22%**	**43%**	**52%**

CO Total (g/kw-hr)	266	162	122

Besides measuring the basic 5 mode emissions test data, the engines were also operated at varying air/fuel ratios at each mode point. Data were taken at the various air/fuel ratio settings to better understand the effects on emissions, running quality, power output, and exhaust gas temperature. Examples of these data are shown in Figures 14 –16 below. Figure 14 shows the emissions concentration values for HC, NOx, and CO over a wide range of air/fuel ratios at Mode 1 for a typical baseline engine. The trends are included here only as an example of the data that were taken as inputs to the catalyst design process and are representative of any typical four-stroke engine.

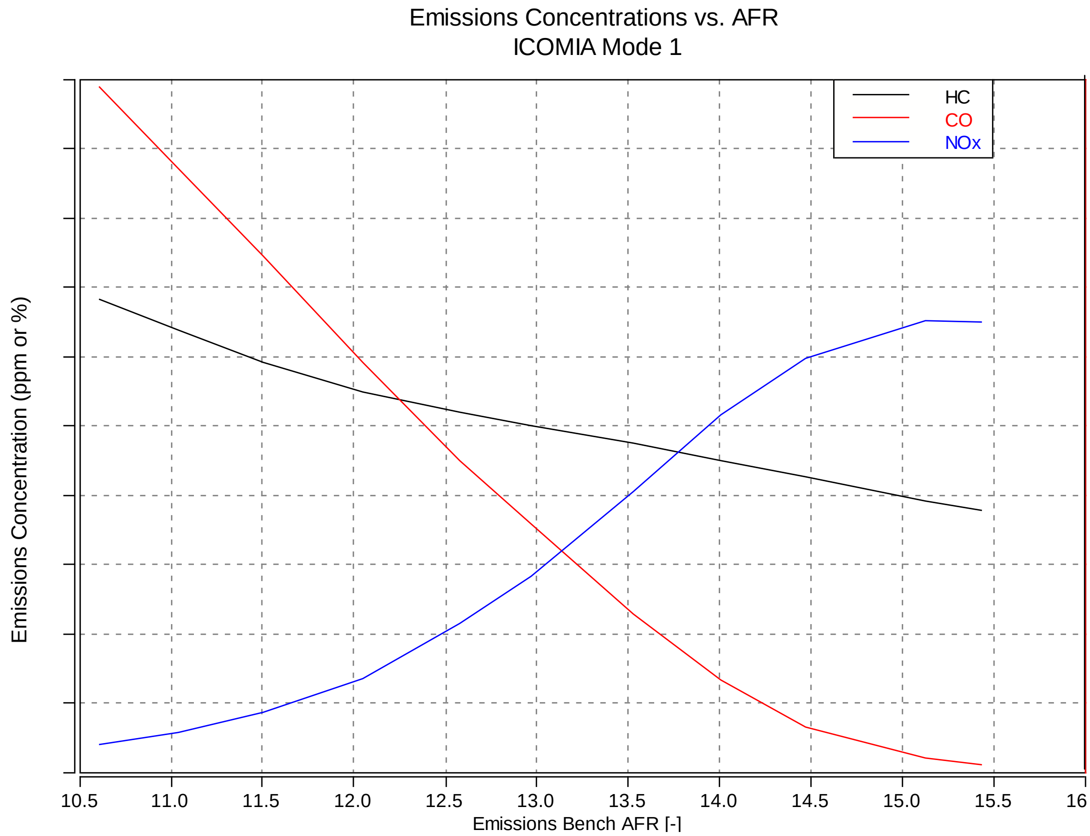


Figure 14: Emissions Concentration Trends vs. Air/Fuel Ratio, Baseline Engine Mode 1 (WOT)

There were many other factors to consider besides the emissions values relative to air/fuel ratio. Figure 15 shows the power output and average exhaust gas temperature measurements from one of the baseline engines at Mode 1. It is clear that the power drops off sharply beyond approximately 13.5:1 air/fuel ratio. The exhaust gas temperature rises steadily as the fueling is leaned out up to approximately a stoichiometric air/fuel ratio. Data such as these helped define air/fuel ratio limits to set the carburetor which would yield acceptable mechanical life for air/fuel ratio sensitive components for the catalyst prototype engines later in the project.

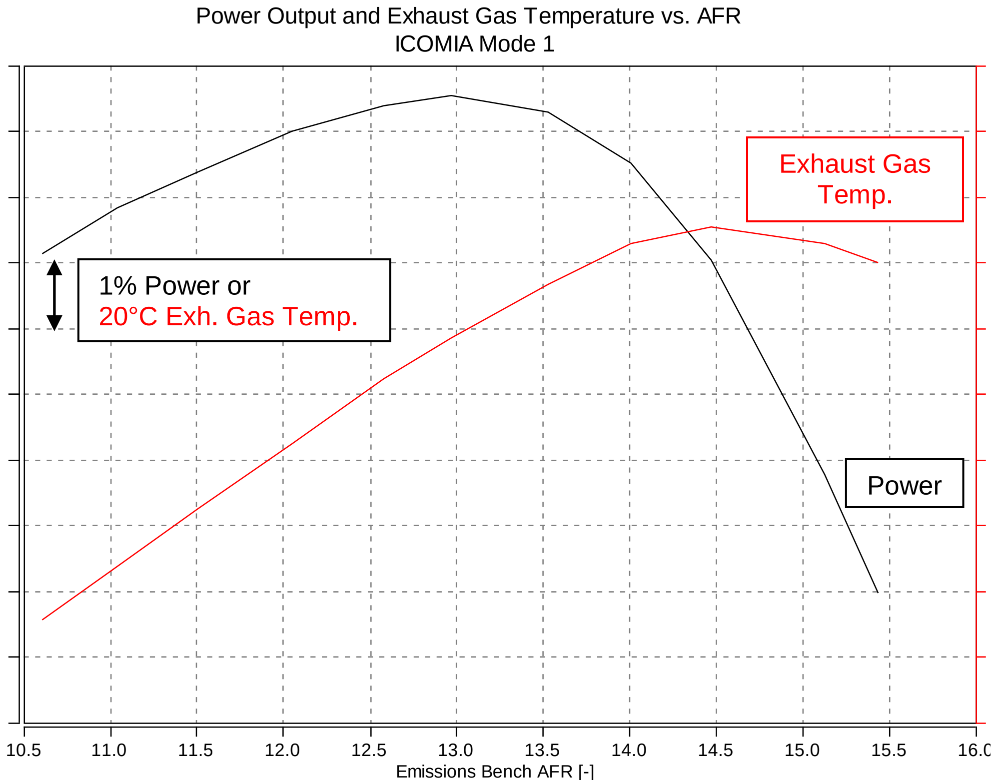


Figure 15: Power and Exhaust Gas Temperature vs. Air/Fuel Ratio, Baseline Engine, Mode 1 (WOT)

Figure 16 shows how the engine running quality related to air/fuel ratio for a baseline engine at Mode 5, which was the idle condition. At air/fuel ratios leaner than 13.0:1, the running quality was dramatically worse. Again, data such as these were generated to aid in setting the carburetor later in the project and to understand/predict the effectiveness of a catalyst to reduce the emissions levels. In the graph, lower numbers indicate better running quality (lower variability).

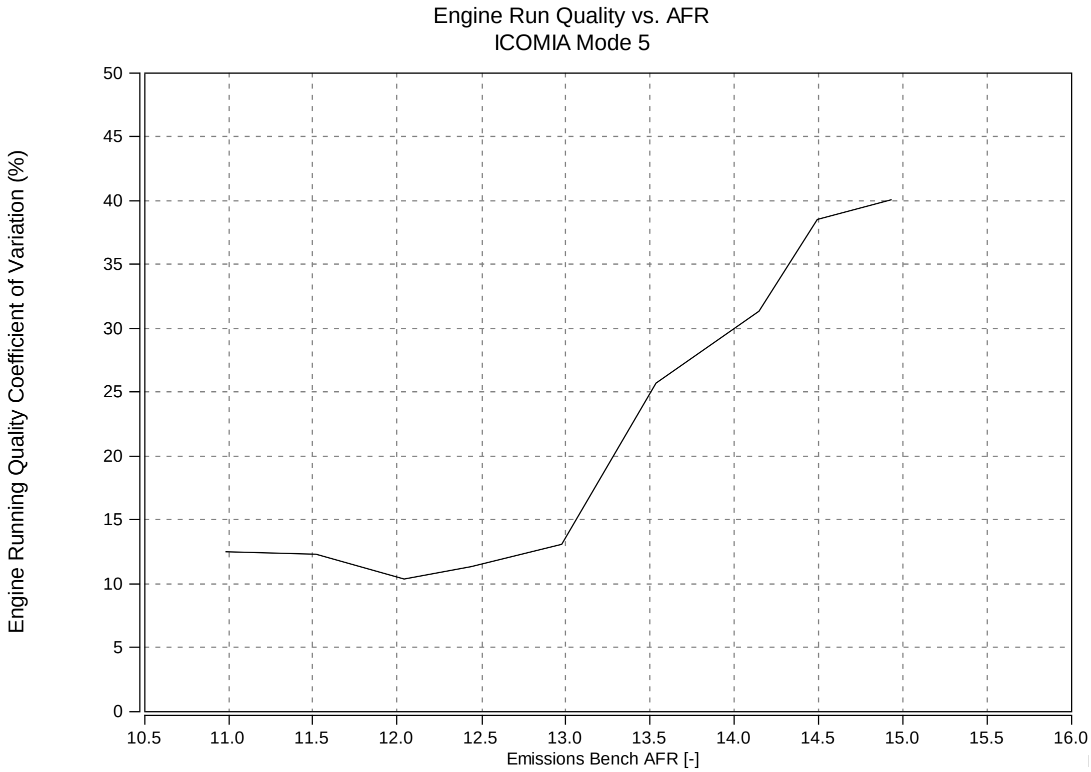


Figure 16: Engine Running Quality vs. Air/Fuel Ratio, Baseline Engine, Mode 5 (Idle)

After collecting the output data from the air/fuel ratio investigation, it was apparent that many factors needed to be considered when adjusting the fueling calibration. This is shown pictorially in Figure 17 below. All of these factors plus the addition of the catalyst conversion efficiency influenced the fueling calibration of the catalyst prototype engines.

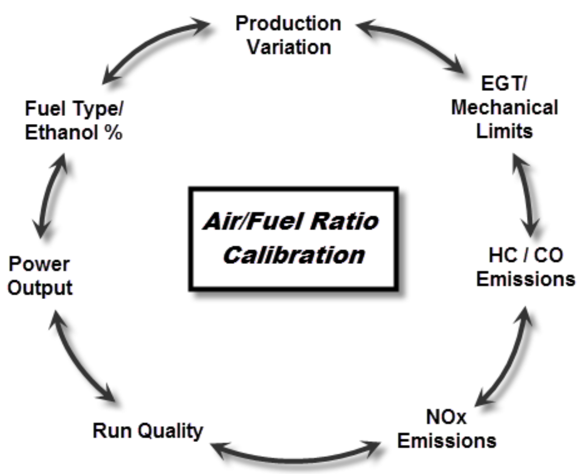


Figure 17: Considerations of Air/Fuel Ratio Calibration

Once the emissions and air/fuel ratio trends were understood, the next step was to measure the effects of increased exhaust back pressure on engine performance due to the addition of a catalyst. An example is shown in Figure 18. The data generated on the baseline, non-catalyst engines were used to develop analytical performance prediction models of the engines. The models were later used to simulate the catalyst exhaust system to predict the engine performance loss due to the increased exhaust backpressure. This was used to help define the catalyst size during the design stage. The analytical performance model also provided exhaust gas flow rate predictions to serve as a boundary condition in the computational fluid dynamic (CFD) analysis of the exhaust system.

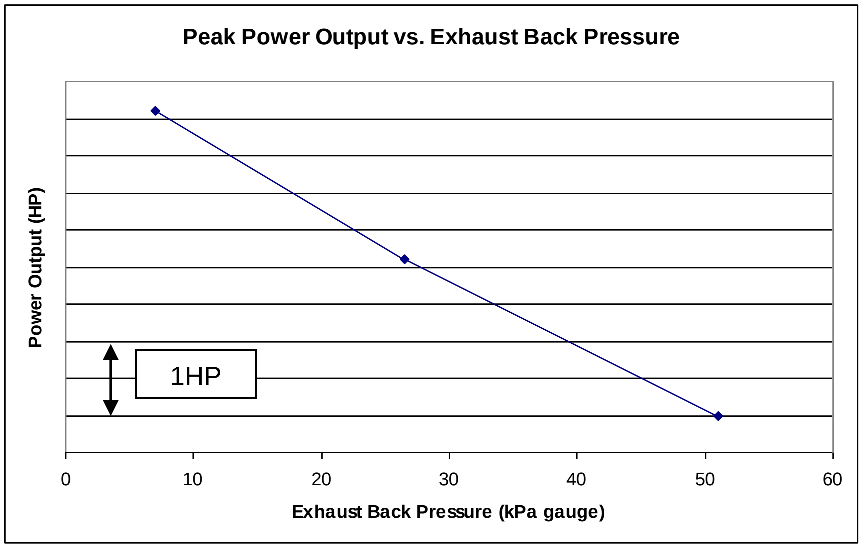


Figure 18: Engine Power Output vs. Exhaust Back Pressure, Baseline Engine

In order to understand if catalyst poisoning was going to be a concern, oil consumption information was gathered for the three small engine families. The oil consumption characteristics were determined by reviewing reference data from past endurance testing programs. This was done in lieu of running a dynamometer test and measuring oil consumption over a short duration since it would have been difficult to accurately measure the small amount of oil consumed by these engines.

Small outboard engines inherently operate with the combustion engines near the water surface. Since the exhaust passage exits into the body of water the engine is operated in and since the cooling water mixes with the exhaust (for most outboards), water intrusion into the exhaust system needed to be considered when incorporating a catalytic converter into the exhaust system. See Figure 19 and 20 for illustration.

Figure 19: Proximity of the Engine to the Waterline

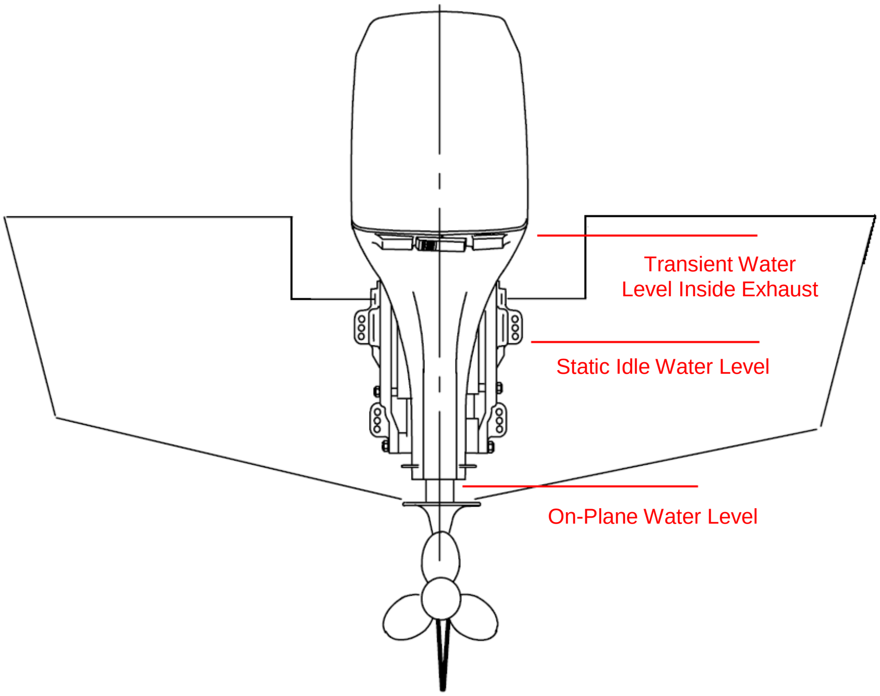


Figure 20: Illustration of Waterline Level at Different Conditions

It should be noted that the failure modes due to water contact on these engines would not have been as immediate as the failure modes of the fully closed-loop fuel controlled large outboard prototypes. The absence of the oxygen sensors, especially the post-catalyst sensor, eliminated any sensor failure modes. The automotive-based oxygen sensors used on current production sterndrive/inboard engines and on the large outboard catalyst prototype engines tend to be extremely sensitive to water contact, typically causing immediate failures. Water contact is much more likely on marine engines than on automotive engines. Water contact with the catalyst element may cause a slight degradation of performance of the catalytic material or cause some corrosion in a metallic substrate. The failure modes in these cases would need repeated exposure occurring over a longer duration to cause a significant or total loss of function.

Testing within this study was performed in test tanks and on boats to determine if water would reach the area of the exhaust system where the catalyst could be mounted. In order to determine how close to the engine the water was getting, the baseline engines were instrumented to measure the water height. The instrumentation inputs were recorded while the engine was operated at various conditions including steady-state speed points and various transient maneuvers. The data were plotted and analyzed to see if there were any indications that the water level came near the engine.

The data showed that the non-catalyzed versions of the small outboards in this study presented difficulty in keeping the exhaust system free from water intrusion where the catalysts were intended to be mounted. All three engine families in this study needed modifications to prevent water intrusion. Solutions were developed and tested on the baseline engines and were implemented on the prototype catalyst engines.

Prototype Design

The design process started by making some basic assumptions/considerations that served as a guide during the development process. The main assumption was that existing engine designs would serve as a starting point and that completely new engine designs were beyond the scope of the project. By having to modify existing hardware, there were limitations on some of the changes that were made. Also, two of the engine families were carbureted and one was equipped with electronic fuel injection, and all had open-loop fueling systems. The basic architectures of the fuel systems were not changed. The design changes were structured within the capabilities of the prototype methods available/selected. The prototype methods were selected to fit within the existing project expense budget. The designs were created in order to balance all of the design constraints. These included optimizing the exhaust flow path, providing adequate cooling to account for the additional thermal load from the catalyst, properly mounting all other components within the existing package space, and overall assembly.

Three engine families were analyzed in this study, which allowed exploration of different design concepts. The final designs for the three engine families were very different. Different catalyst substrate materials were used, which necessitated different catalyst mounting strategies. Though the designs made in this project were not “production-ready”, the designs were intended to simulate exhaust systems that would be feasible for production. In this way, the emissions reduction potential of production-feasible designs was determined. There were several design considerations that needed to be incorporated to best simulate production-feasible designs that were unique to the small outboard designs compared with the design of the large outboard. Since some of the small outboards were used in applications that required them to be portable, weight and package size were important factors. In order to simulate a production design, the engines were developed to simulate the limitations imposed by production processes typically used on these types of engines.

Determining the basic design of the catalysts was the first step in the design process and several basic types of catalyst substrates were considered. Metallic foil catalysts were in use in current production sterndrive/inboard applications so the technology was familiar. The metallic foil catalysts were expected to have good mechanical durability and have relatively low backpressure, but were generally more expensive and were more prone to corrosion failures. The ceramic catalysts were thought to be more cost effective, tolerate higher temperature and have superior corrosion resistance. There were concerns about the ceramic catalyst due to higher back pressure and the mounting durability concerns experienced in the large outboard test. Since three engine families were available to test, the decision was made to use both ceramic and metallic elements. Given the concerns over the ceramic catalyst mounting, only one engine family was selected to use a ceramic element. The 6HP engine family utilized ceramic catalyst elements. The 20HP and 40HP engine families were designed to incorporate metallic catalyst substrates.

The catalyst sizes for these engines were larger relative to the exhaust flow rate than the previous outboard research project. The main reason for selecting a specifically larger catalyst was the difference between the open-loop fuel systems on the small engines versus the closed-loop fuel control systems on the large outboards. The target volumes, in combination with a table of the standard substrate sizes offered from the substrate suppliers, were used to determine several size options for each engine family. The various combinations of length and diameter were used as potential solutions during the design process and the final sizes were selected based on packaging, flow development and other considerations.

The final design details in specifying the catalysts were to select the cell density, washcoat, and precious metal loading. The cell densities used varied between 400 cpsi and 600 cpsi, depending on the availability of standard substrate sizes. The washcoats used on the substrates were based on commercially available automotive washcoat technologies. The amount of precious metal loading on each catalyst design was within the range of the amount used on current production sterndrive/inboard engines.

Once the details of the catalysts for each engine family were known, exhaust system routing concepts were developed with 3D CAD models. The various concepts were compared and the best design was selected using a concept selection matrix that ranked the options based on functional requirements and attributes. By using this process, the concept that was the best compromise of all the functional requirements was selected.

The selected concept was then further refined to add the details necessary to produce the prototype engines. The main areas of focus in the detailed design portion of the process were the exhaust system routing and the cooling system. Computer aided engineering techniques were applied to both of these aspects of the design. Computational fluid dynamic analysis software was used to understand the fluid flow of both systems. In addition, conjugate heat transfer (CHT) methods were employed to predict the temperatures throughout the system.

In order to ensure the best possible emissions reduction performance, the gas flow through the catalyst was analyzed using CFD. The CFD model was used to understand the catalyst utilization. In addition to optimizing the emissions reduction of the system, optimizing the flow through the catalyst also minimized the exhaust back pressure increase due to the catalyst and reduced catalyst aging. Optimizing all of these parameters led to a design that minimized cost and packaging space. The targets and methodologies used in analyzing the catalyst utilization were derived from the analyses used in creating the current production catalyzed sterndrive/inboard engines. Figure 21 below shows an illustration of the flow modeling performed on one of the exhaust systems.

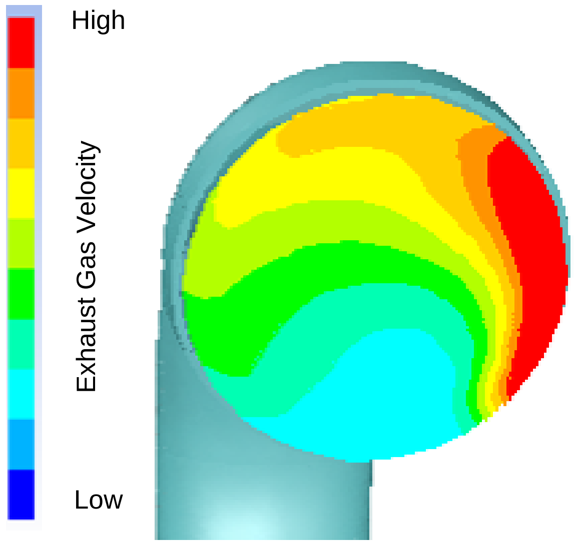


Figure 21: CFD Analysis of Exhaust Gas Flow

As mentioned above, computer aided techniques were also employed to understand the cooling system performance and refine the design. The first step was to analyze the coolant velocities in the components and compare the prototype catalyst designs to the current production designs. Figure 22 shows an example of the coolant velocity analysis. Once the coolant flow velocities were refined, thermal inputs were added to the models and analyzed again to predict the temperatures of the coolant, exhaust gases, and the material temperatures of the components. Figure 23 shows an example of the temperature profile.

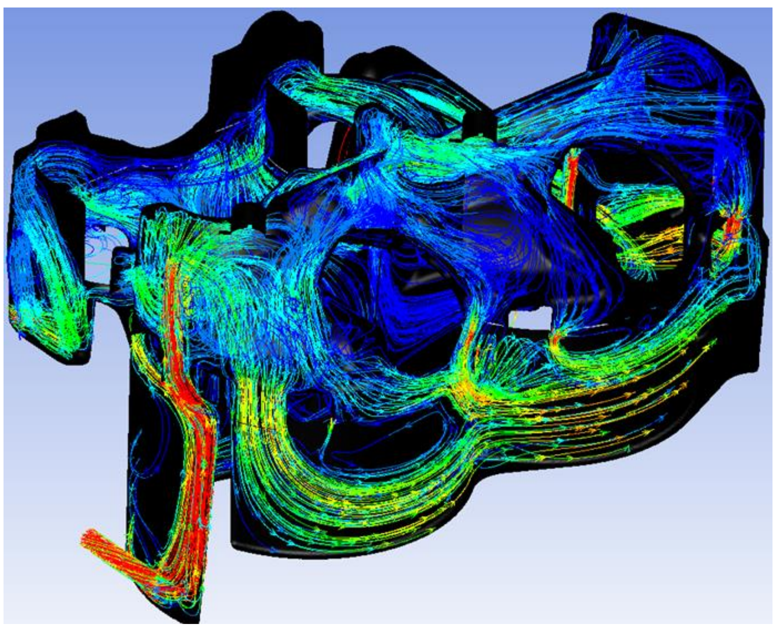


Figure 22: Coolant Flow Velocity Pathlines

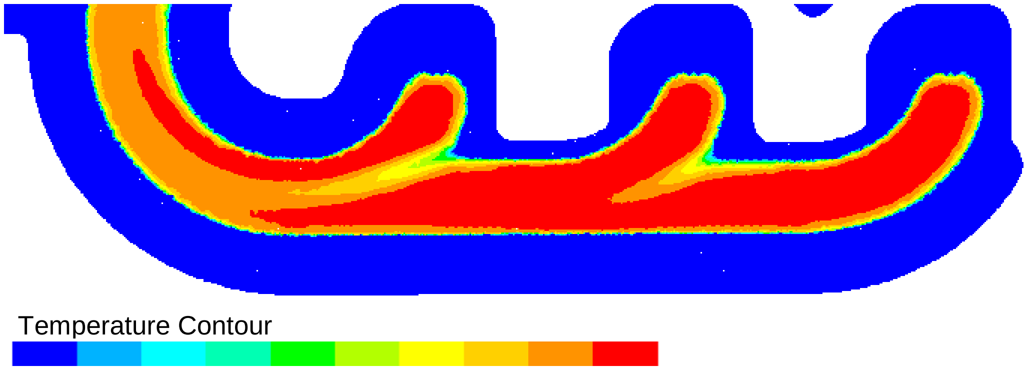


Figure 23: Exhaust Gas Temperature Contour Plot

Once the design work was completed, the impact to the overall cost of the products and the cost of the tooling required to make the new designs was investigated. The cost of the tooling required for each engine family would be significant. The new designs of these three engine families required new tooling to be created for some or all of the following components: cylinder blocks, cylinder heads, top cowls, lower cowl pans, driveshaft housings (multiple lengths for each engine family), brackets, etc. Mercury currently offers four-stroke models from six unique engine families in the under 50HP segment.

Engine Build

After the design process was completed, prototype hardware was constructed. The prototype process began by purchasing brand new, randomly selected, current production, non-catalyst engines. Four engines of each engine family type were purchased to serve as surrogates to be modified to accept the catalyst design modifications. The engines were built in accordance with the specifications determined during the design process described above. Prototype parts were made from investment castings and machined billet aluminum. Prototype gaskets made from either fiber materials or rubber coated metal to seal the various joints. Many of the original castings, including cylinder blocks, cylinder heads, driveshaft housings and portions of the cowling, required modification. In addition, many of the hoses and wires were replaced or modified to allow rerouting to accommodate the modifications to the base engine hardware. To provide for alternate mounting locations for some of the electrical components, new brackets were fabricated. Note: An overview of the basic components of an outboard marine engine is shown in the Appendix.

To construct the 6HP prototype engines, portions of the engine and the driveshaft housing were modified and prototype pieces that created the necessary modifications of the assembly were machined from aluminum billet material. Portions of the cowling assembly were modified to create the necessary space to house the larger catalyst exhaust system. The modifications to the engine design also included making the necessary changes determined by the water intrusion testing. Once all the pieces were created, the assemblies were test fit using pressure-sensitive film to verify adequate clampload on all the gasketed joints. The overall fuel/induction system and the ignition system were not modified (aside from carburetor settings/adjustments).

Much like the 6HP engine, construction of the 20HP engines included machining billet aluminum parts and modifications to some of the production castings. Other components were also made using prototype investment castings. The cylinder heads, cylinder blocks, and driveshaft housings all required modifications. Prototype gaskets were made by laser cutting the base materials. There were a number of metal core gaskets used which also required the sealing beads to be formed with prototype tools. Again, the gasketed joints were checked with pressure sensitive film to ensure good sealing. The carburetor (aside from settings/adjustments) and induction systems were unmodified. Several peripheral components were displaced due to the addition of the catalyst exhaust and were relocated. The ignition system retained a majority of the stock components. However, the control module needed to be relocated due to packaging and required a different mounting bracket and a different wire harness to accommodate the changes. The only undercowl area that the bracket could possibly be placed resulted in the bracket blocking access to the spark plugs. This was not a production-feasible arrangement, but was deemed acceptable for this prototype engine design. Other hoses and wires needed to be rerouted or lengthened to accommodate the necessary exhaust system changes. Modifications necessary to prevent water intrusion were also incorporated into the final configuration. Some of the cowling components required modification to provide clearance, but otherwise fit.

Most of the major 40HP components that were newly designed were cast using a prototype investment casting process. Several major engine castings, such as the cylinder block and cylinder head, needed significant modification to conform to the catalyst design. During the assembly process, several fasteners were difficult to access. Although acceptable for the prototype project, these areas would not be acceptable for production manufacture. Several pieces of the stock cowling components needed modification to clear the modified components but otherwise fit. The stock top cowls needed some of the sound damping foam removed from the inside to allow installation. There were still some areas where components rubbed on the top cowls, so the clearances would not be acceptable for production engines. The ignition coils and the electrical mount plates containing the relays and voltage regulators were displaced by the exhaust modifications. New brackets were constructed to relocate the electrical components. As a result, the wire harnesses were modified to accommodate the new locations and longer spark plug wires were made. There were many other hoses and wires that needed to be rerouted on the engines, which became very congested areas. The congested routings were acceptable for the prototype engines, but would not be acceptable for production engines.

Once all of the prototype engines were built, they were weighed to understand the effects from the catalyst systems. The 6HP engine weight increased by 2 lbs. The 20HP engine experienced a 20 lbs. weight increase. However, 5 lbs. of the weight increase was due to the addition of some componentry required only for prototype construction. Considering the fact that the extra componentry was only required due to the packaging limitations imparted by using a production engine for the basis of the prototype, the weight of those pieces should be neglected. However, even if the weight of those pieces was neglected, the additional 15 lbs. of weight caused the total engine weight to exceed the limit of what Mercury would consider a portable engine. This would likely be a significant detriment to the market's acceptance of the catalyst version. The 40HP engine increased 15 lbs. over the current production design.

Development Testing

Running engine testing followed shortly after the completion of the engine assembly. Dynamometer development and evaluation was the starting point for the testing. The primary purpose of the dynamometer evaluation was to prepare the engines for endurance testing. As such, there were two areas of focus when testing was conducted on the dynamometers. The first area was to validate the mechanical systems of the engines, which consisted mostly of assessing the cooling system performance. The cooling systems were affected more directly than any of the other mechanical systems on the engine due to the additional heat input from the catalytic reactions. Once the mechanical systems were validated, the fuel system calibration occurred. The calibration was necessary to deliver the best emissions performance while maintaining acceptable running quality and making sure no temperature limits or other hardware limitations were exceeded.

In order to perform the development on the cooling and fueling systems, the engines were thoroughly instrumented. The engines used for cooling system development were instrumented with thermocouples in the cooling jackets and also in several locations embedded in the metal in key locations (near gasketed joints, etc.). Key locations in the exhaust system were also fitted with thermocouples to measure the gas temperatures and the catalyst bed temperatures. Several locations were instrumented throughout the coolant passages to measure the pressure in the system. The fuel system calibration engines were fitted with emissions measurement probes upstream and downstream of the catalysts to be able to determine the catalyst conversion efficiencies. The emissions bench used in testing measured HC, NOx, CO, CO_2 and O_2. Fuel flow was measured on a mass basis using a fuel balance. The engines were also fitted with in-cylinder pressure indicating equipment. The cylinder pressure transducer was connected to a combustion analyzer to record and analyze key combustion parameters. Emissions testing was done with EEE fuel (EPA Tier II emissions reference grade fuel), but some of the calibration work was also performed with E10 fuel since E10 was used during the boat endurance testing.

Cooling system testing included running the engine under steady-state conditions at set speed/load points. The test consisted of running the engine at the emissions mode points and then running the engine at WOT through a wide range of speeds. Data were logged showing the various temperatures and pressures throughout the cooling system.

During the fuel system calibration, the carburetor or EFI system was adjusted to deliver varying air/fuel ratios to measure the effects on emissions and other critical parameters, such as torque output, exhaust gas temperature, catalyst temperature, and running quality. Once the trends for the emissions and other critical parameters were understood, the fuel system was tuned at each mode point to deliver the best overall balance of emissions performance, running quality, and engine hardware limitations (ex: catalyst temperature). The fuel system calibration process mainly followed the standard ICOMIA points, with other part load and full load points sampled to make sure the calibration was robust.

The 6HP engines were the first to be tested on the dynamometer. The first engine was run through a break in cycle with an inert catalyst. The inert catalyst substrate was used to make sure the catalyst mounting techniques were acceptable before installing the loaded catalyst. It was also noted that the surrounding metal temperatures were acceptable without the additional thermal loading from the catalytic conversion. The engine was disassembled to verify the mounting of the catalyst and then a loaded catalyst was installed. The engine was tested at full power while measuring the metal temperatures, coolant water temperatures, and exhaust gas/catalyst temperatures. The data showed that the metal temperatures were very similar to the metal temperatures on the baseline non-catalyst engine that was tested initially. As a result, no modifications were made to the cooling system for any of the 6HP engines.

The cooling system test engine was then operated at the emissions mode points, again taking the thermocouple data. Testing was performed using the as-received carburetor, so no air/fuel ratio adjustments were made and this was reflected in the emissions results. The catalyst mid-bed temperature data indicated there was sufficient temperature to keep the catalytic reactions active at the low speed, light load points (Modes 4 and 5). A temperature of 350°C was generally considered to be the minimum temperature to sustain catalytic activity. However, since the air/fuel ratio was relatively rich at Modes 4 and 5, the conversion efficiencies of the HC and CO were very low due to lack of oxygen availability. The NOx emissions were very low at Modes 4 and 5 so the total HC+NOx at those modes was dominated by the influence of the HC emissions. The lack of HC conversion at Mode 5 was significant since this idle condition alone can contribute over 5 g/kw-hr of HC emissions, which is more than the 5-mode total CARB 4-Star limit for sterndrive/inboard engines.

Once the cooling system was validated on the 6HP engines, calibrating the carburetor for better emissions was the next step. To accomplish the carburetor calibration, the next engine was installed on the dynamometer. The typical break in and power runs were performed on the calibration engine. Many permutations of carburetor setups were tested on the calibration engine and cooling system engine. Changes included various main jets, pilot jets, emulsion tubes/main nozzles, and idle mixture screw settings. Changes were tested on several carburetor bodies to be sure changes were consistent carburetor-to-carburetor. Test-to-test and day-to-day variability made the calibration process very difficult and inconsistent. There was up to 0.3 - 0.4 air/fuel ratio variation day-to-day without altering the carburetor at certain mode points. The variability seemed to be affected by variations in ambient air conditions and undercowl temperatures, though no clear trends were evident. In addition, the changes made at one mode point affected the fueling rate at other mode points. For example, a change in main nozzle and main jet that was intended to lean out the fueling at Mode 2 would lean out operation at Mode 1 beyond the acceptable range. Likewise, an adjustment to the idle mixture screw to change idle (Mode 5) would also affect the air/fuel ratio at Mode 4. In general, the changes made to the carburetor were intended to run leaner air/fuel ratios at most of the mode points compared to the stock carburetor, especially at Modes 4 and 5.

The resultant HC+NOx emissions output of the stock and modified carburetors can be seen in Table 7. The carburetor modifications intended to lean the carburetor calibration significantly reduced the HC and CO emissions, but slightly raised the NOx emissions. The overall post-catalyst HC+NOx emissions were reduced more than 50%. The largest change in HC occurred at Mode 5 (idle) due to the carburetor adjustments. However, comparing the pre- and post-catalyst HC results at Mode 5, it was clear that there was little to no catalytic conversion occurring. The reductions made in HC emissions were simply a result of the engine-out HC emissions dropping due to the lean air/fuel ratio. The same improvements at Mode 5 would occur on a non-catalyst engine if the same change to the carburetor was made.

Table 7: Five-Mode Total Emission Results, Post-Catalyst, 6HP Carburetor Calibration

Carburetor Calibration g/kw-hr	**HC+NOx**	**CO**
Stock Carb. Post-Cat.	15.3	220
Modified Carb. Post-Cat.	7.0	125

During the course of the cooling system development and fuel system calibration, the power output of the engines was also measured. The addition of the catalyst reduced the torque output across a broad engine speed spectrum. This reduced both the peak torque and peak power output of the engine. The power output of the four catalyst prototype 6HP engines was between 0.3 - 0.7HP below the reference non-catalyst engine. This engine type is one model of a family of engines that include 4HP, 5HP, and 6HP variants. With performance loss of over 0.5HP, the 6HP catalyst engine performance would be closer to that of the current production, non-catalyst 5HP engine.

Like the 6HP development testing, the cooling system evaluation occurred first on the 20HP development testing. Several issues with the first version of the prototype cooling system configuration were identified. There was too much restriction in the system leading to significant pressure loss and insufficient cooling water flow rate. The first configuration also had significant thermostat temperature cycling at idle.

The lack of water flow caused the engine to run coolant temperatures above the thermostat set point. Significant changes were made to the prototype cooling system to reduce restriction and allow the water flow rate to increase. Concurrently, the thermostat was modified to reduce the temperature cycling at idle. After the first round of modifications, an issue was found with the cylinder head cooling. A portion of the prototype exhaust passage in the cylinder head had excessive metal temperatures so the cooling jacket was modified to address the issue. The change to the water jacket was tested and validated. The last step in finalizing the prototype cooling system on this engine family was to check for overcooling, which was completed and showed no issues.

Once the prototype cooling system was performing adequately, the calibration of the carburetor occurred. Less overall calibration work was necessary on the 20HP carburetor than the 6HP carburetor since the 20HP carburetor had a leaner overall calibration to start with. A main jet change was desired to get leaner operation at Mode 2. Changing to the next leanest main jet size caused the engine to run too lean at Mode 1. As a result, main jets of the same nominal size as the production carburetor were hand selected by measuring the inside diameter of the passage and then testing them on the running engine to measure the resultant air/fuel ratio. In order to lean out Modes 4 and 5, the idle mixture screw was adjusted. Hand-selecting main jets in this manner and the fine adjustments to the mixture screw were acceptable for this research project in order to get consistent results, but would not be an acceptable approach for production. The production carburetors would be expected to have much more engine-to-engine variability than what was experienced in this project.

A comparison of the overall emissions output with a production and a modified carburetor for the 20HP engine is shown in Table 8. Since the carburetor adjustments caused the engine to run leaner at most of the mode points, the HC and CO emissions were reduced, both pre-catalyst and also post-catalyst. Even with the leaner calibration, the CO conversion efficiency remained relatively low since all mode points operated rich of stoichiometry The NOx emissions increased significantly pre-catalyst (making the overall pre-catalyst HC+NOx higher), but only slightly higher post-catalyst. Since the stock carburetor setup was close to the desired settings, the improvement realized with the modified carburetor was not as drastic as the change seen on the 6HP engine.

Table 8: Five-Mode Total Emission Results, Post-Catalyst, 20HP Carburetor Calibration

Carburetor Calibration Emissions Comparison [g/kw-hr]	**HC+NOx**	**CO**
20HP Stock Carburetor	6.7	160
20HP Modified Carburetor	5.0	83

The power and torque outputs of the 20HP catalyst engines were approximately the same as the reference engine. It is possible that the modified exhaust passage of the catalyst system decreased the exhaust back pressure, compared to the non-catalyst version, by approximately the same amount that the catalyst itself increased the flow restriction. Another possible explanation may be that the leaner carburetor settings on the catalyst engines may have caused the engine to operate closer to the optimal air/fuel ratio for best torque.

The first 40HP dynamometer development test engine had additional instrumentation to measure temperatures associated with the cooling system. The test data showed that the catalyst temperatures at idle were below the light-off temperature and the interior walls of the manifold were cold enough to form condensation inside the exhaust passage. Modifications were made to the coolant flow path to increase the catalyst temperature and the interior wall temperatures. These changes did not appreciably change the catalyst temperature. However, the changes caused insufficient cooling water flow in other areas and caused boiling and significant temperature cycling. Several other iterations were tested until a system was found that kept the interior walls warm enough to prevent condensation in the exhaust runners, but kept water temperatures cool enough to avoid boiling. This design did not have high enough temperatures to sustain the catalyst above the light-off temperature, however. None of the configurations tested, even the most extensive changes, had catalyst temperatures at or above the light-off temperature at idle. There was also some thermostat cycling present at some of the part-load operation points so modifications were made to address the cycling issue.

After cooling system development, the calibration was optimized for the catalyst. With the EFI system on the 40HP engine, calibration efforts were more straight-forward. The engine calibration program was adjusted using a computer and the engine controller programming software. In this case, Mode 1 and Mode 5 were left essentially unmodified. Mode 1 was left unchanged due to exhaust gas temperature and other hardware limitation concerns. Mode 5 was unaltered due to driveability and idle stability concerns. The calibration efforts lowered emissions output of all constituents. After the calibration effort was complete, the resultant HC+NOx total was 4.3 g/kw-hr and the CO total was 80 g/kw-hr. It should be noted that even with the EFI system, there was measurable day-to-day variability in air/fuel ratio. Though the magnitude of the changes in air/fuel ratio observed were less than those of the carbureted engines, the variability of the 40HP engine still affected the emissions output.

The wide open throttle torque output of the 40HP engines was measured during the dynamometer evaluation. The catalyst system reduced the torque output in the upper speed ranges when compared with the benchmark engine. The loss in peak torque was approximately 2% and the loss in power was approximately 5%, on average. This was likely due to the increased exhaust back pressure from the catalyst substrate and the longer exhaust path length.

Endurance Testing

Two engines from each engine family were endurance tested on two different test cycles. The first engine from each family was run at wide open throttle in a test tank for 100 hours (referred to as "WOT endurance"). This was done mainly to verify the integrity of the prototype hardware. Once confidence was gained in the hardware, the boat endurance testing commenced and consisted of 350 hours of a customer usage duty cycle based on the ICOMIA mode points. The boat endurance tests included the necessary emissions measurements to determine the emissions deterioration factor.

The 6HP WOT endurance engine completed 100 hours of testing without any durability issues of the prototype hardware. The gaskets had no leaks and the catalyst and mount mat material were intact and showed no evidence of movement. The prototype pieces remained intact and caused no failures.

Though the durability of the hardware was acceptable, the combustion parameters were not. The engine was found to be low on power after the tank endurance approximately 0.7HP. For reference, reviewing prior power results for non-catalyst endurance engines showed that the peak power stayed within +/- 0.2HP of the initial value. After interrogating the data further, a reduction in airflow was identified as a likely cause of the loss in power. The loss in power was not due to a change in exhaust back pressure based on a comparison of exhaust back pressure data taken before and after endurance. This indicated that catalyst plugging was not likely the cause of the airflow changes.

Since the airflow characteristics of the engine changed, the air/fuel ratio delivered by the carburetor changed. The largest change in air/fuel ratio was observed at Mode 4, where the air/fuel ratio went from 14.3:1 prior to endurance to 11.8:1 after endurance. Mode 4 was particularly sensitive to changes in airflow because the edge of the throttle blade would either be over or past one of the holes in the progression circuit. Subtle changes in throttle plate angle during Mode 4 testing yielded large changes in air/fuel ratio as a result.

Following the post-endurance dynamometer testing, the 6HP tank endurance engine was disassembled for inspection. As mentioned above, the prototype hardware appeared to be in good condition. Significant amounts of deposits were found on the piston crown, combustion chamber, and valves, as shown in Figure 24. The deposits on the valves and combustion chamber were significant enough that they could have affected the performance loss due to restricted flow. The amount of deposit build up was not an expected result based on prior experience endurance testing the non-catalyst version of this engine family. The effects of the increased back pressure due to the catalyst and thus the amount and/or temperature of residual exhaust gas left in the chamber may have influenced the deposit build up.

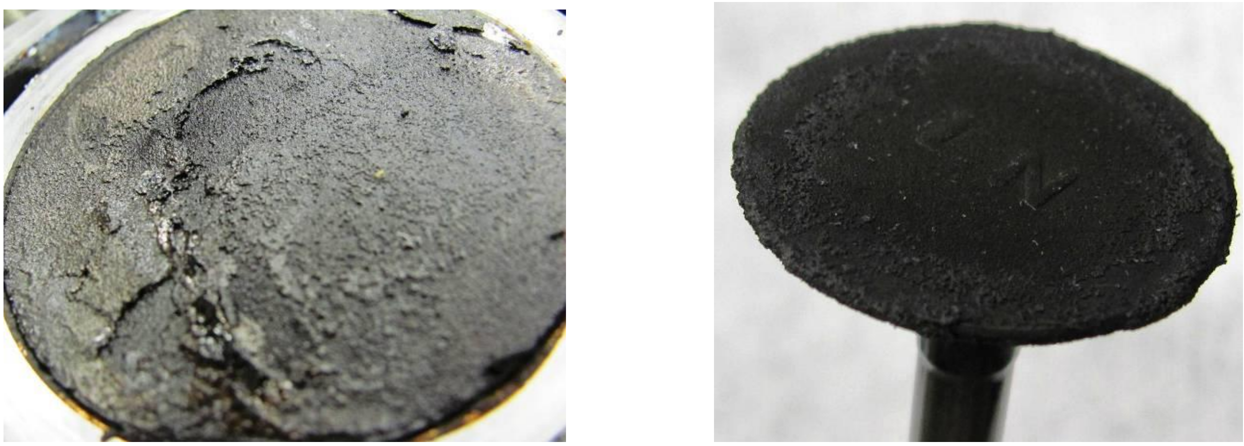


Figure 24: 6HP WOT Tank Endurance Piston Crown and Intake Valve Deposits

Once the WOT tank endurance test was completed, increasing the confidence in the durability of the prototype hardware, boat endurance testing commenced. The boat endurance vessel can be seen in Figure 25. The boat used for the test was a 14' Carolina Skiff flat bottom boat. The total boat endurance duration was 350 hours operating with a customer usage duty cycle to approximate the ICOMIA cycle. The emissions were measured at the beginning, middle, and end of the endurance test.

Figure 25: 6HP Boat Endurance Vessel

The 6HP boat endurance test engine completed the first half of the endurance test and was returned to the dynamometer test facility to measure the emissions output. Upon running the engine on the dynamometer, operation at idle was found to be very lean and causing running quality problems. After several other checks, the idle mixture screw was removed, finding significant deposit build up. The idle mixture screw was replaced with a new piece and adjusted to attain the correct/baseline air/fuel ratio at idle using the emissions bench to calculate the air/fuel ratio. The emissions deterioration values of HC+NOx and CO were within expected ranges once the idle mixture was set appropriately. The replacement and subsequent readjustment masked any effects of fuel system drift/variability of the mode points affected by the mixture screw (idle being one of the main contributors to the total HC+NOx value). It should be noted that there were several recorded incidents of stalling during the boat endurance test, likely exacerbated by the lean settings of the carburetor. The carburetor was likely set leaner at idle than what would be tolerable for a production engine as evidenced by the engine stalling.

The 2nd half of the endurance test was completed and the engine was sent back to the dynamometer test facility for the final power and emissions check. The engine power dropped approximately 10% through the course of testing, much like the WOT tank endurance test engine. [Note: Lower power results would cause higher calculated emissions, all else equal, since the emissions were calculated on a specific basis.] The 5-mode total HC+NOx and CO results for the emissions tests throughout the endurance test can be seen in Figures 26 and 27. The HC+NOx increased considerably by the end of the endurance test, starting from 7.1 g/kw-hr and going to 11.1 g/kw-hr. The largest change was observed between the midpoint and endpoint. The CO emissions also increased, but somewhat more consistently throughout the duration of the endurance testing. The CO emissions were 118 g/kw-hr prior to endurance testing and rose to 144 g/kw-hr by the end of the boat endurance test.

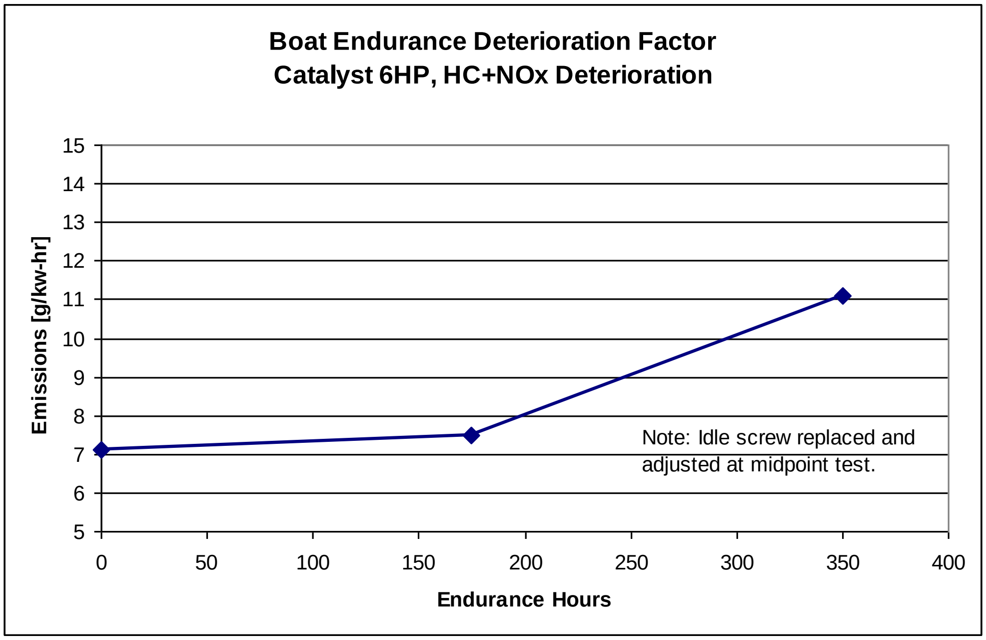


Figure 26: 6HP Boat Endurance Post-Catalyst HC+NOx Emissions

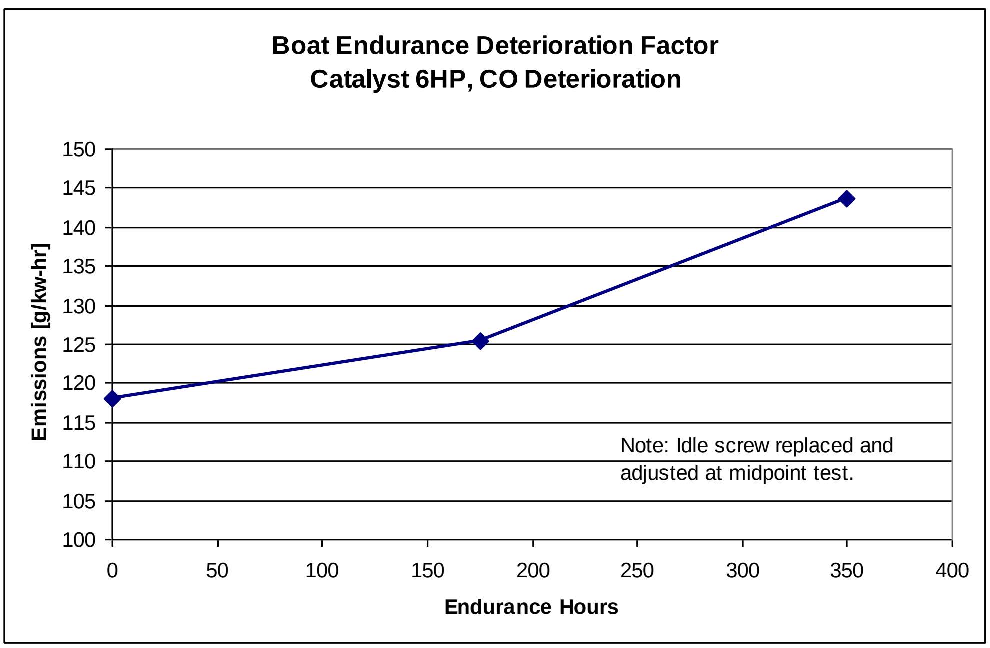


Figure 27: 6HP Boat Endurance Post-Catalyst CO Emissions

In order to better understand the emissions output, the air/fuel ratio was plotted for each mode point. Figure 28 shows the air/fuel ratio from each test. The air/fuel ratio was leaner at four of the five mode points during the midpoint test compared to the pre-endurance test, yet the HC emissions were higher at the midpoint than at the initial measurement.

Overall, most of the mode points of the endpoint emissions test were richer than the pre-endurance test, leading to even higher HC and CO values.

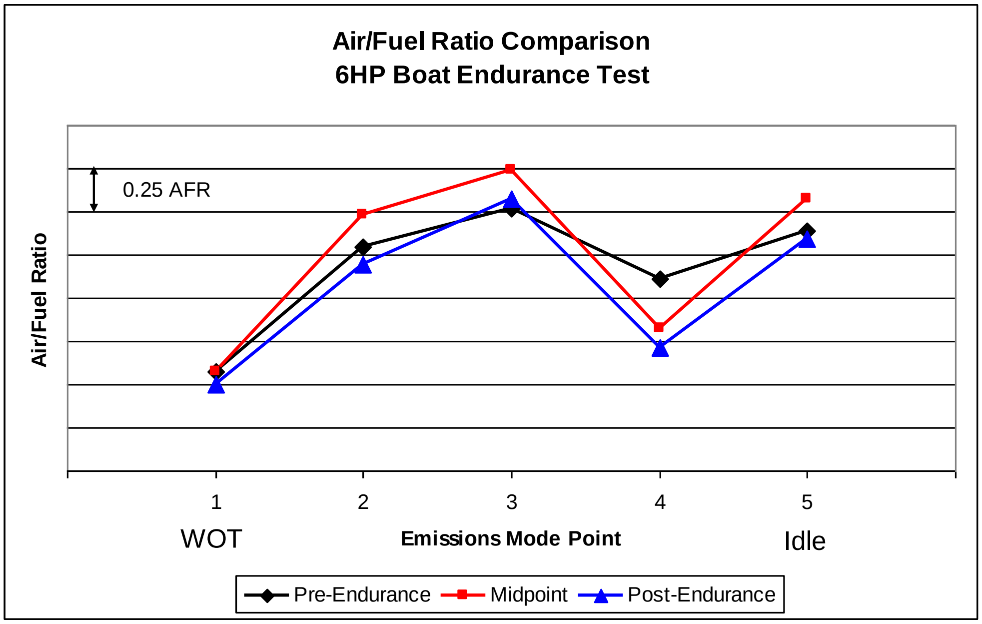


Figure 28: 6HP Boat Endurance Air/Fuel Ratio Trends

After the dynamometer testing was completed at the end of the endurance test, the engine was disassembled and inspected. No issues were found with the hardware. The catalyst and mount mat did not rotate or slide in the housing as there was no evidence of movement. The catalyst was not cracked, chipped, or plugged. See Figure 29. The mount mat showed no signs of deterioration or charring/burning.

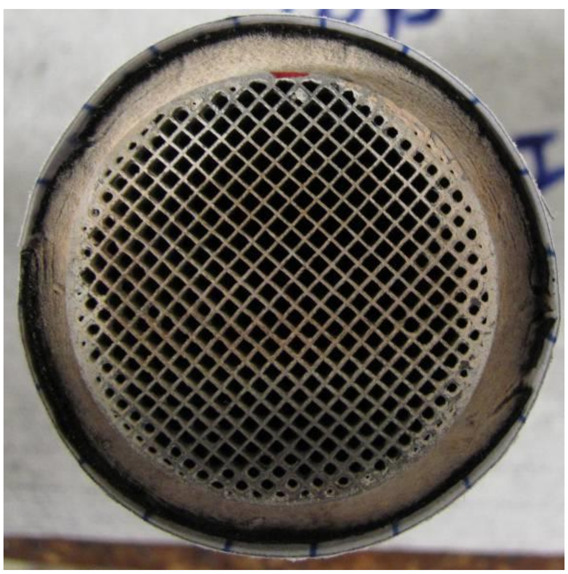


Figure 29: 6HP Boat Endurance Catalyst Inlet Face, Post-Endurance

Similar to the WOT tank endurance engine, the 6HP boat endurance showed appreciable deposit build-up on the piston crown, combustion chamber, and a portion of the exhaust passage. It is likely that the deposits contributed to the increase in engine-out hydrocarbon emissions. The deposits were analyzed in the materials lab to determine the composition. The lighter colored deposits were identified as sodium, magnesium, chlorine, and calcium; indicating salt build-up from the ambient environment during the boat test. Analysis of the darker deposits suggested that the oil was a potential source of the deposits since carbon was identified as the main component with trace amounts of magnesium, phosphorus, sulfur, calcium and zinc. See Figure 30.

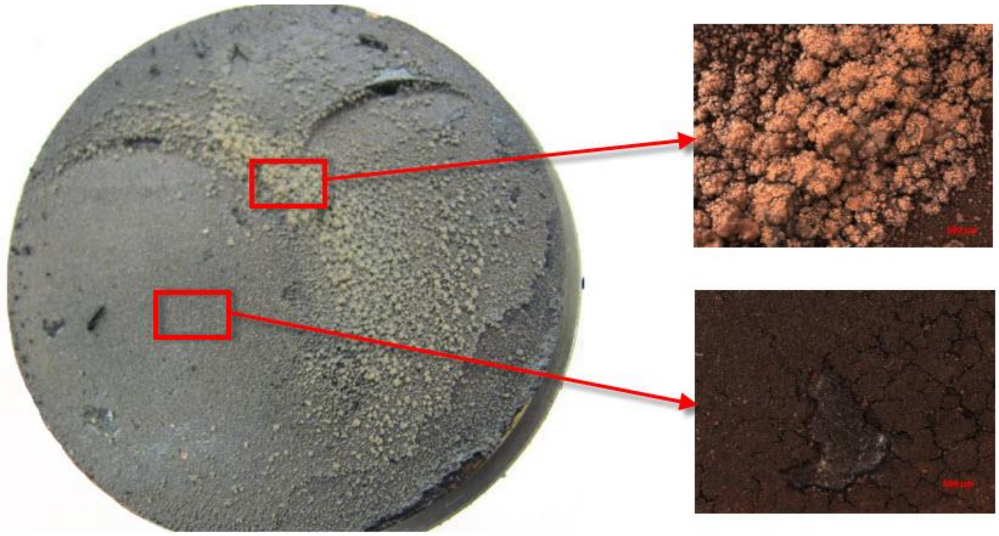


Figure 30: 6HP WOT Tank Endurance Engine Piston Crown Deposits

Both 6HP endurance engines had appreciable performance loss when comparing the before and after results. The results are shown in Figure 31. Both endurance engines were disassembled and inspected after testing. The only notable issue related to performance loss identified during the end of test inspection was the amount of carbon deposits, which may have led to valve shrouding and low airflow.

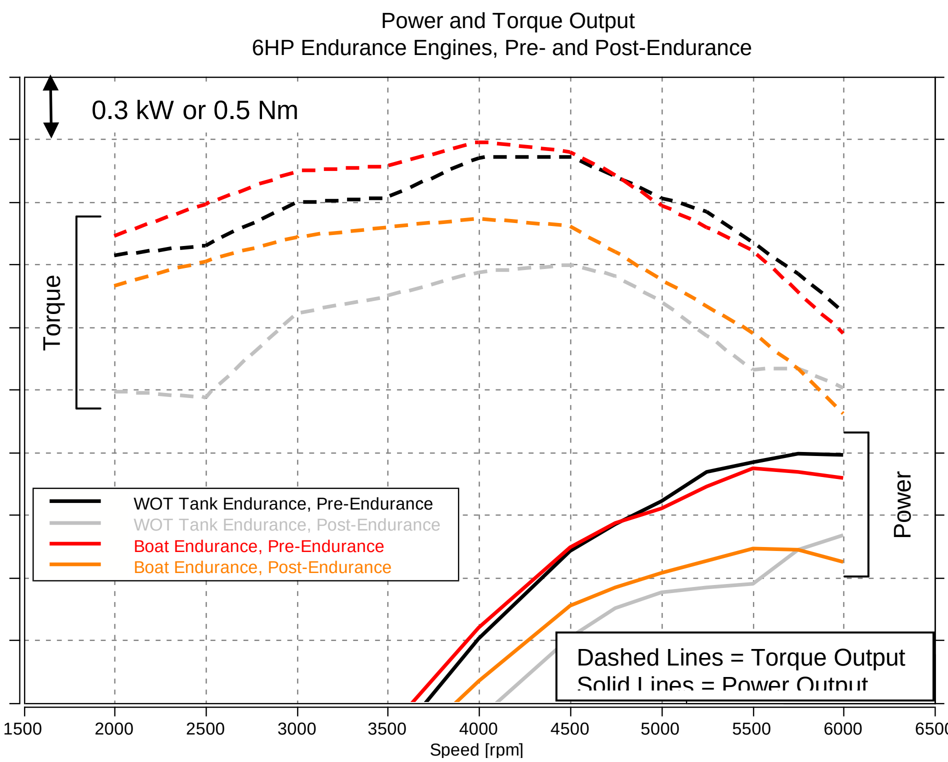


Figure 31: 6HP Endurance Engine Performance Comparison

In order to test if the carbon deposits were the cause of the performance loss, the WOT tank endurance test engine had the combustion chamber surfaces cleaned and the engine was reassembled. The engine was again performance tested and the results are shown in Figure 32 below. Cleaning the deposits influenced the volumetric efficiency, and therefore, the torque output of the engine. Although the test did not fully restore the performance, it demonstrated that the deposits did influence the volumetric efficiency, which had a direct impact on the torque output. As stated previously, the exhaust backpressure did not change appreciably during the course of the endurance test so catalyst plugging was not the cause. However, the influence of the increased exhaust gas temperatures and pressures of the catalyst version relative to the non-catalyst version may have contributed to the increased rate of deposit formation. The performance loss and amount of deposits were not expected results based on prior experience from running non-catalyst engines of the same family.

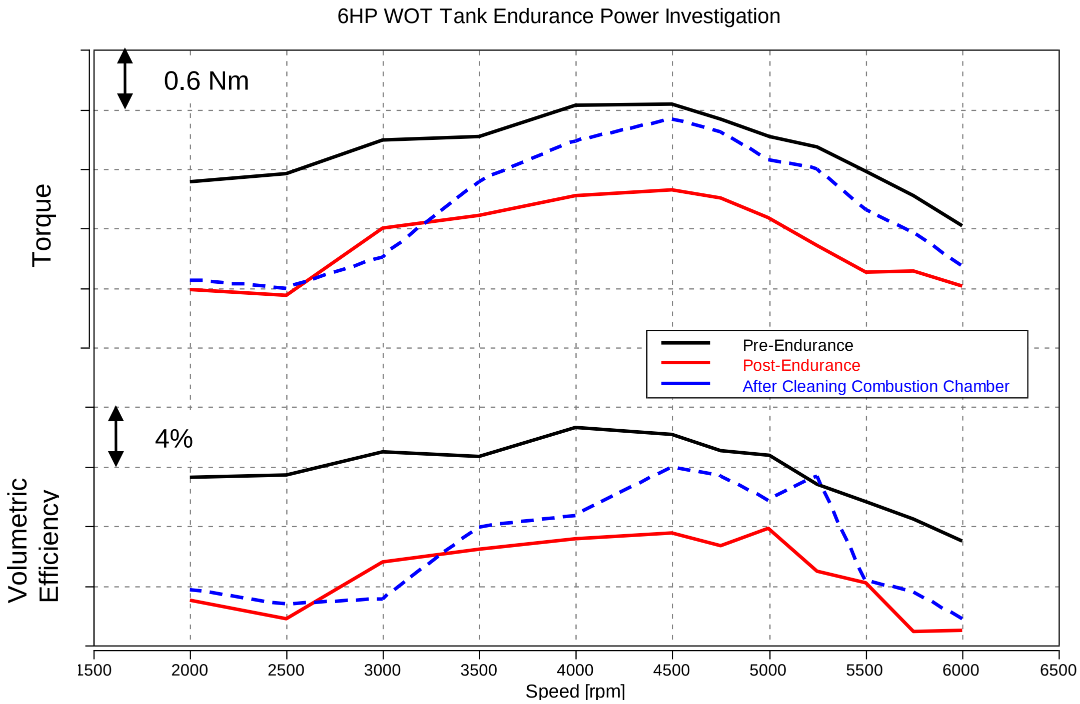


Figure 32: 6HP Endurance Engine Performance Before and After Cleaning Deposits

The prototype 20HP WOT tank endurance engine performed the 100 hours of WOT endurance without any issues. The prototype pieces and gaskets all held up without any failures or leaks.

Since no prototype hardware issues were experienced during the WOT tank endurance test, the 20HP boat endurance engine was placed on test. A photograph of the test vessel is shown in Figure 33. The vessel used for testing was a 12' Sea Ray tender.

The boat endurance test engine successfully completed the 350 hour test with relatively few incidents. Most of the issues encountered during testing did not influence the catalyst system (instrumentation issues, etc.). There was, however, an issue with the carburetion that did influence the emissions testing. Approximately 100 hours into the endurance test, the test driver noted that the engine stalled repeatedly at idle/low speed (stalling approximately every 5 minutes). In order to diagnose the problem, the choke was engaged slightly to see if the stalling was caused by lean operation. The stalling went away when the choke was engaged. Based on the issues with the 6HP idle mixture screw, the idle circuit was immediately suspect on the 20HP carburetor. The idle mixture screw was inspected and it was confirmed that the position had not changed relative to a mark on the carburetor body since initial calibration prior to endurance testing. The idle mixture screw was removed, cleaned, and reinstalled in the same position as was marked prior to removal. However, no significant debris or contamination was found when the mixture screw was cleaned. The engine was placed back on test with no further instances of stalling encountered. When the engine was returned to the dynamometer test facility for the midpoint emissions check, the air/fuel ratio was found to be significantly different at idle despite the fact that the mixture screw was installed in the same position. The mixture screw was readjusted to deliver the same idle air/fuel ratio as the original emissions test. The readjustment of the idle mixture screw masked any effects at low speeds/loads of air/fuel ratio drift due to the endurance testing.

Figure 33: 20HP Boat Endurance Vessel

The overall HC+NOx results from the 20HP boat endurance test are shown in Figure 34 below. The HC+NOx value started at 5.8 g/kw-hr but fell to 4.7 g/kw-hr by the end of the endurance test. The CO emissions increased sharply from the initial reading to the midpoint and then fell slightly from the midpoint to the endpoint. The CO values were, from start to finish, 108, 130, and 125 g/kw-hr. The results from the CO measurements are shown in Figure 35.

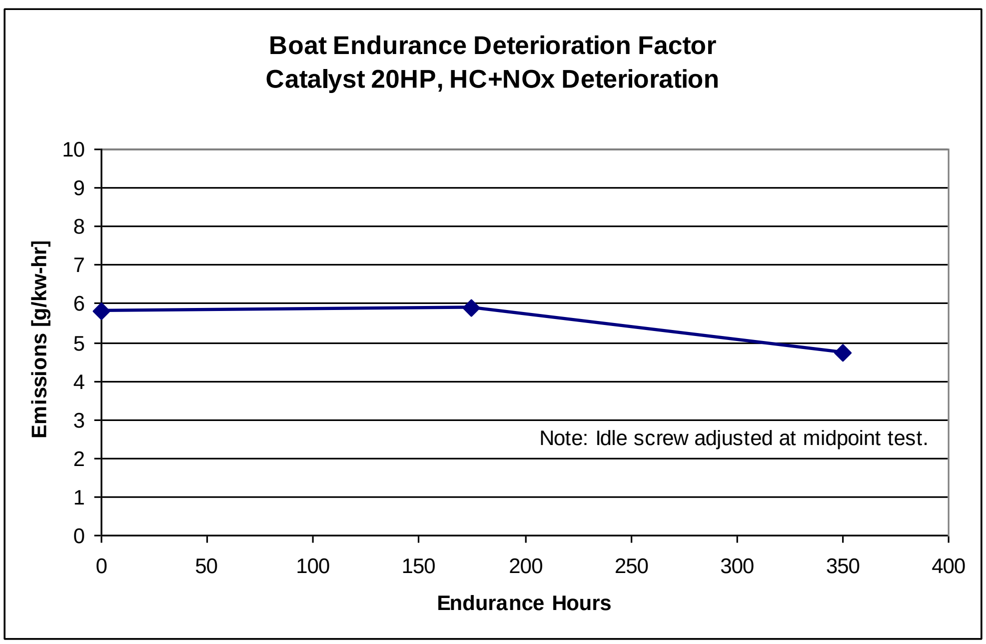


Figure 34: 20HP Boat Endurance Post-Catalyst HC+NOx Emissions

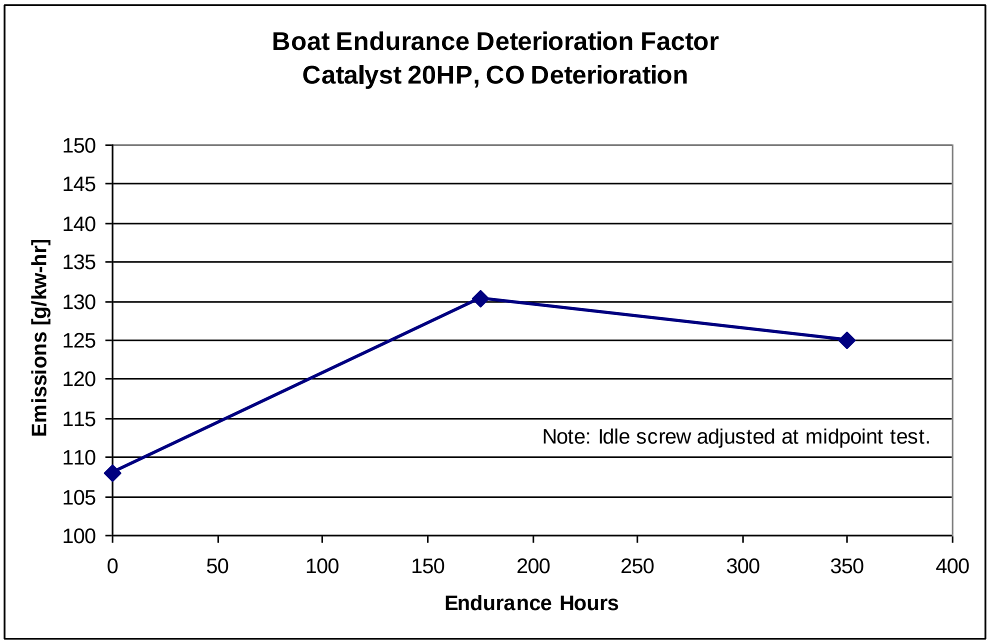


Figure 35: 20HP Boat Endurance Post-Catalyst CO Emissions

More investigation was necessary to understand the emissions results. In order to get to the next level of understanding, the air/fuel was plotted against each mode point. The results are shown in Figure 36 below. The air/fuel ratio drifted rich of the original test at Modes 1-3 for the mid- and endpoint emissions tests. The air/fuel ratio at Modes 4 and 5 were reasonably matched from the original test and midpoint test. The engine ran leaner at Modes 4 and 5 during the final emissions check, despite the fact that the idle mixture screw was not adjusted between the two measurements. The biggest driver for the reduction in HC+NOx comparing the pre- and post-endurance values was the reduction in HC emissions due to the lean air/fuel ratio shift at Modes 4 and 5.

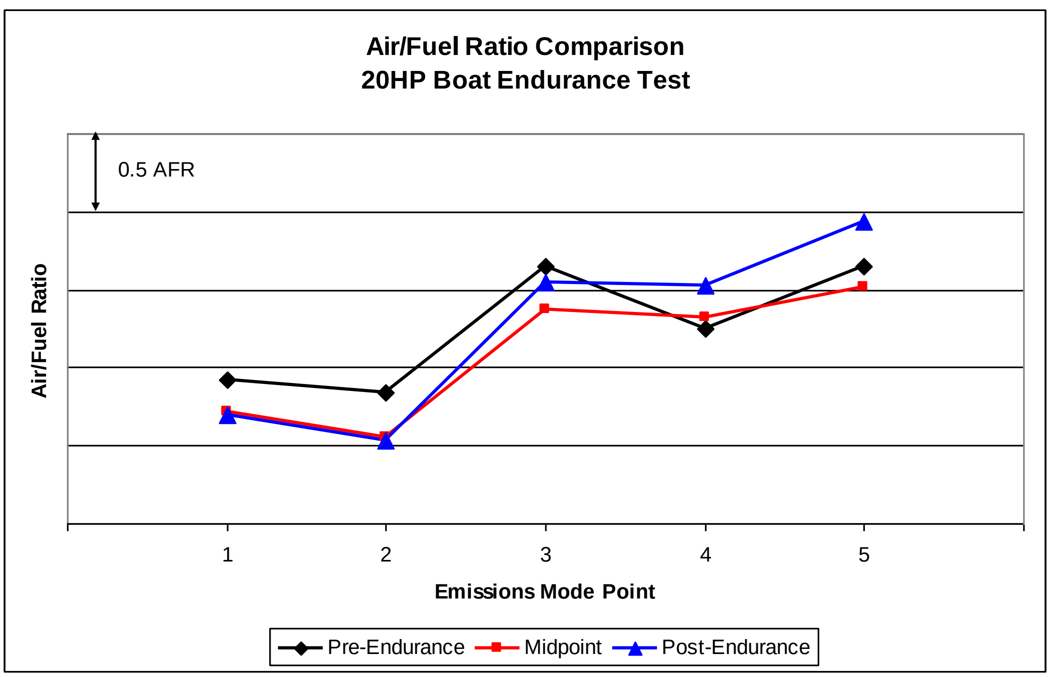


Figure 36: 20HP Boat Endurance Air/Fuel Ratio Trends

Despite running richer at Modes 1-3, the post-catalyst hydrocarbon emissions were approximately the same at all of the tests. The biggest differences were observed at Modes 4 and 5. The main reason that the overall HC+NOx emissions were lower during the final emissions check was because the HC was lower at Modes 4 and 5 because the carburetor drifted lean. Generally, the CO trends were consistent with expectations considering the changes in air/fuel ratio. The biggest changes in CO occurred at Modes 1-3 as a result of running more fuel-rich during the midpoint and endpoint emissions measurements.

In addition to the emissions, the engine performance measurements occurred at each interval through the endurance test. The results are shown in Figure 37 below. The torque output was nearly identical when comparing the pre-endurance and midpoint measurements. However, the endpoint measurement data showed that the engine lost approximately 1 Nm output throughout the speed range tested. This was considered an acceptable amount of performance loss for a research project so no further investigation was performed.

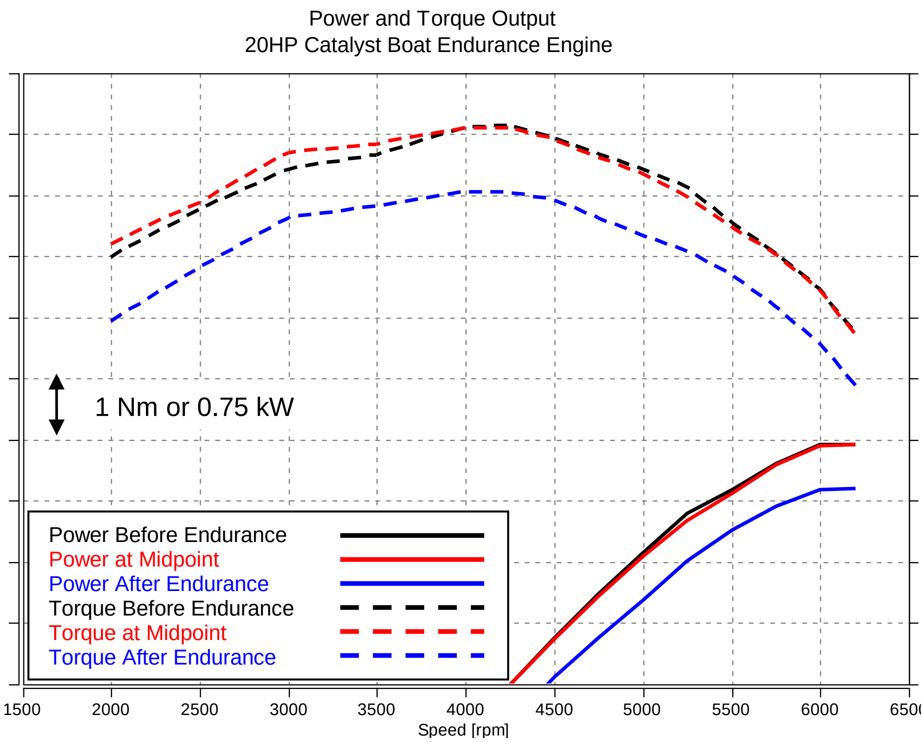


Figure 37: 20HP Boat Endurance Engine Performance Comparison

In general, the 20HP boat endurance hardware looked to be in good condition after testing. There were a few areas of the catalyst foil that showed minor flaws, likely caused by thermal conditions. A photograph of the inlet face of the catalyst is shown in Figure 38 below. None of the flaws found would be considered significant and the catalyst appeared to be in good overall condition. There were some piston crown deposits on the 20HP engine, but not nearly to the extent of the 6HP deposits. The 20HP pistons showed similar build up that appeared to be salt deposits like on the 6HP piston. The combustion chambers and valves had very little deposit build up.

Figure 38: 20HP Boat Endurance Catalyst Inlet Face – Post-Endurance

Like the other two engine families, endurance testing on the 40HP engine began with the 100 hour WOT tank endurance test. The 40HP WOT tank endurance engine ran through testing without a single recorded incident. The prototype castings and gaskets performed as intended with no issues.

Once confidence was gained in the hardware during the WOT tank endurance test, the 40HP boat endurance engine was sent to the boat test facility. The engine was rigged on a 16' Key Largo center console boat shown in Figure 39 below. The 350 hour customer cycle endurance test was completed without major incident. The only recorded incident logged during testing was due to an instrumentation issue with the oil pressure data acquisition hardware.

Figure 39: 40HP Boat Endurance Vessel

Figures 40 and 41 below show the HC+NOx and CO data at various intervals of the endurance test. In both graphs, the emissions output was highest at the midpoint emissions check. The air/fuel ratio control was the critical parameter in the emissions output. The air/fuel ratio values are shown in Figure 42 below. The engine ran more fuel rich at every mode point when comparing the data from the initial and midpoint test. During the last emissions test, the engine ran leaner at Modes 3 and 5 compared to the midpoint test. Based on the air/fuel ratio trends, the HC emissions would be expected to be highest at the midpoint test points. However, Modes 1 and 2 HC emissions showed little sensitivity to changes in air/fuel ratio. This is likely an indication that the engine-out HC emissions at high speeds/loads dropped as the engine accumulated run time, despite the changes in air/fuel ratio. The HC emissions variation at the test intervals was driven primarily by Modes 3-5 where it is evident that the engine ran leaner at the endpoint than at the midpoint. Considering only the air/fuel ratio trends, the lowest NOx emissions would be expected during the midpoint test. This, however, was not the case. The post-catalyst NOx actually increased between the initial measurement and the midpoint test, especially at Modes 1 and 2. It is unlikely that the engine-out NOx emissions increased considering the air/fuel ratio shift. The increase in post-catalyst NOx was due to catalyst deterioration. The CO output followed the trends expected when considering the air/fuel ratio data at each test interval.

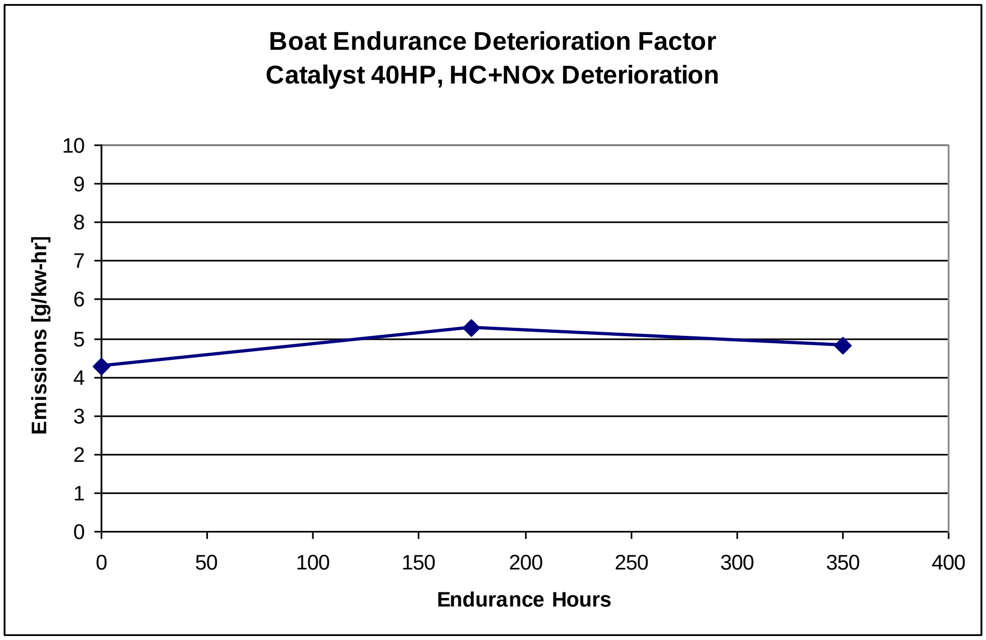


Figure 40: 40HP Boat Endurance Post-Catalyst HC+NOx Emissions

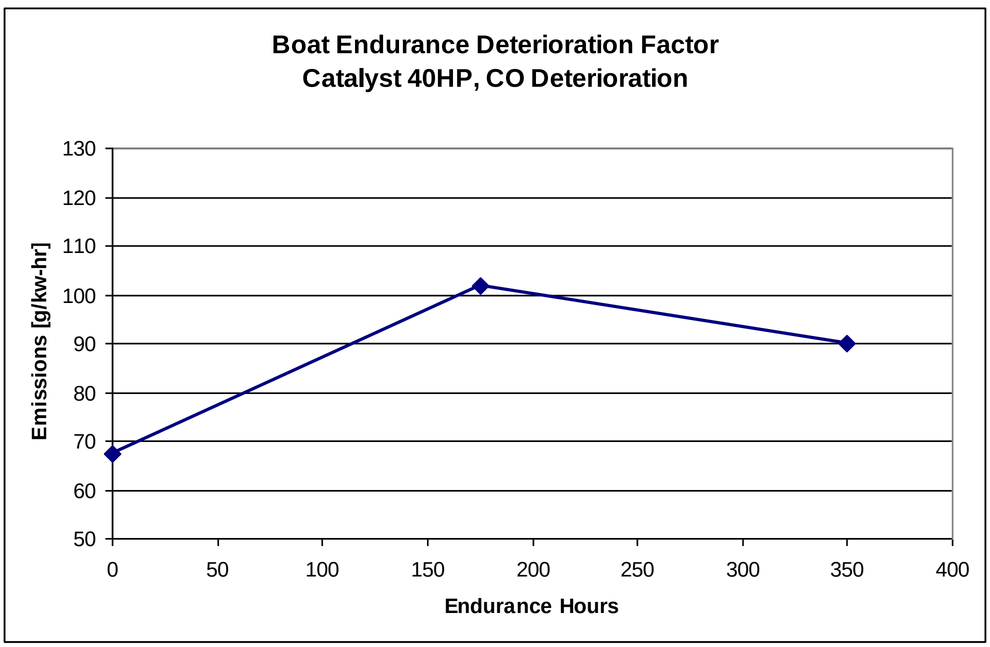


Figure 41: 40HP Boat Endurance Post-Catalyst CO Emissions

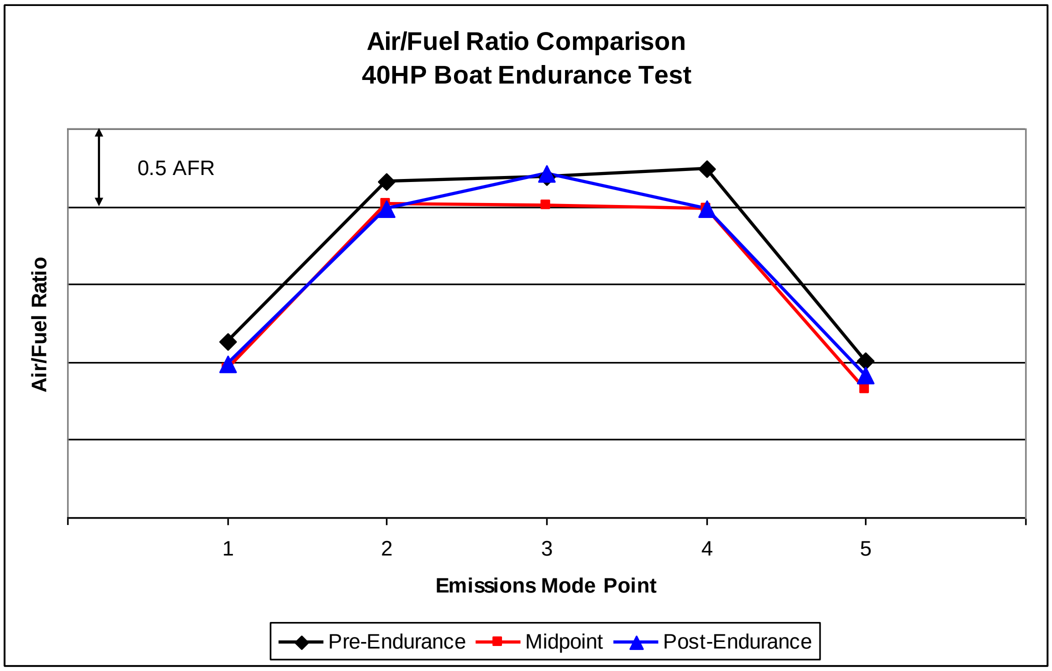


Figure 42: 40HP Boat Endurance Air/Fuel Ratio Trends

In addition to measuring the emissions, the power output of the 40HP boat endurance engine was measured before and after the endurance testing. The power and torque values remained within expected ranges of change so there were no issues.

Following the boat endurance testing, the components were disassembled for inspection. Overall, the hardware appeared to be in good condition. Figure 43 shows a photograph of the inlet face of the catalyst. In general, the catalyst was in very good shape and showed no signs of excessive temperatures. There were a few areas of the catalyst matrix that showed some distortion or other evidence caused by the high temperatures normally experienced in the catalyst. In addition to inspecting the catalyst, the remainder of the exhaust system was inspected. There were some minor mineral deposits in the cooling passages, but nothing beyond what was expected. The exhaust passage downstream of the catalyst was also inspected for evidence of water intrusion, but there was no evidence of any water intrusion.

Figure 43: 40HP Boat Endurance Catalyst Inlet Face – Post-Endurance

Emissions Variability Estimate

The effects of air/fuel ratio on emissions became very evident during the fuel system calibration processes and subsequent endurance testing of the three small engine families. In order to better understand the impact this sensitivity would have on the overall emissions output of production engines, an estimate was made using data from several sources and the process involved several steps. The basic process involved estimating the air/fuel ratio variability using data from emissions audits of non-catalyst production engines and combining them with the post-catalyst emissions data from various air/fuel ratio settings on the prototype engines. Only estimates for HC+NOx were generated with this analysis and deterioration was not included. Since the CO conversion efficiency dropped to near zero in rich operation with the catalyst system, it was expected that under the worst-case conditions the post-catalyst CO emissions would essentially equal the engine-out CO emissions.

In order to understand the variability that could be expected in air/fuel ratio control, data from the last several years of emissions audits were analyzed. The air/fuel ratio for each engine family was compiled and sorted by mode point. Statistical analysis was performed for each mode point to determine the average and standard deviation of the data set. The assumed range expected in future production audits was +/- 3 standard deviations (sigma). The 6 sigma approach was used in order to predict over 99% of the range expected in the total population with high confidence. The results of the air/fuel ratio analysis for the 20HP engine are shown below in Figure 44 as an example. In general, the total 6 sigma variation was approximately 2 – 3 air/fuel ratio points for most (not all) mode points. Idle tended to have the highest variability which exceeded the 2 – 3 air/fuel ratio range typical of the other mode points. It should be noted that the carburetors and fuel systems of the engines used in this study were very typical for engines of this type/size. The amount of air/fuel ratio variability observed in this study is likely very representative of other four-stroke outboard engines of similar size. [Note: Since this method used existing emissions audit data, only non-ethanol emissions reference fuel was used in testing. This method did not include the effects of ethanol blended fuel.]

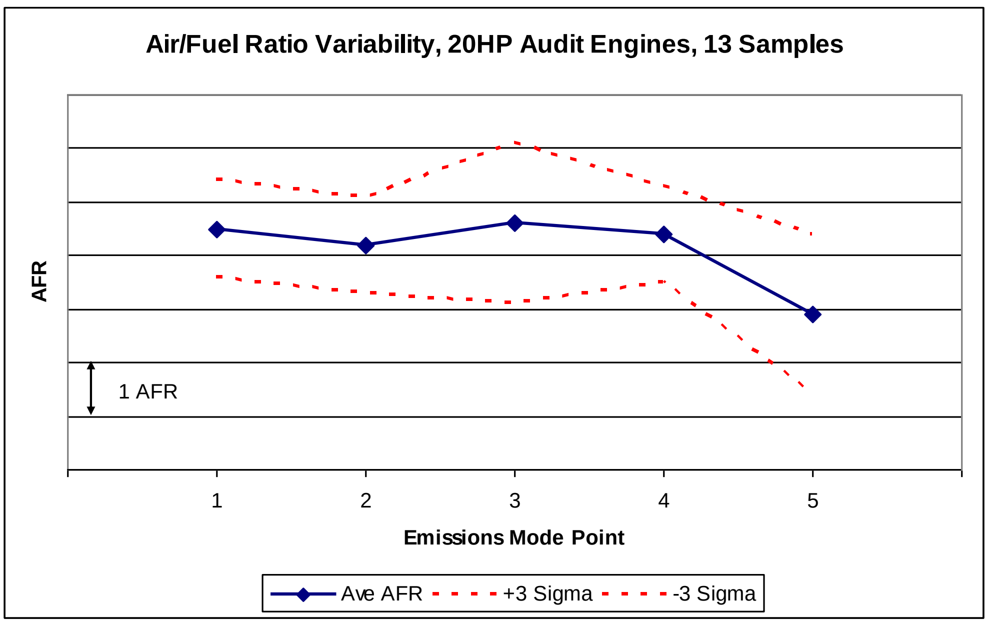
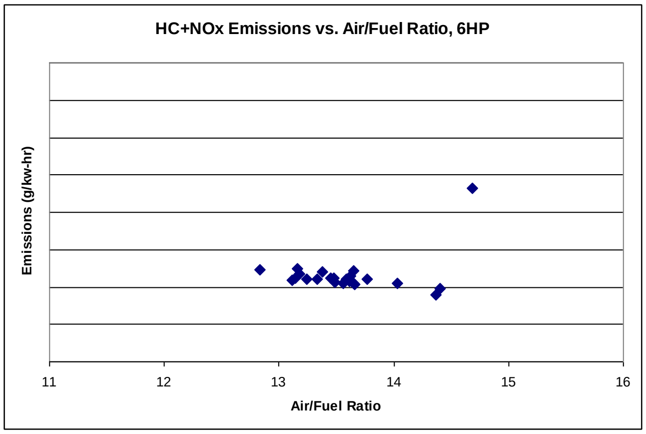


Figure 44: 20HP Air/Fuel Ratio Variability

The next piece of information determined was the resultant post-catalyst emission output as a function of air/fuel ratio using the prototype engines. Two approaches were used to gather these data. The emission output vs. air/fuel ratio of the 40HP engine was determined with a direct test since varying the air/fuel ratio was straight-forward using the EFI system. The engine was operated at varying air/fuel ratios at each mode point and the resultant emissions output was measured. Due to the difficulty in precisely controlling the air/fuel ratio at each mode point with a carburetor, direct testing was not feasible on the 6HP and 20HP engines. In these cases, data collected during the carburetor calibration process were gathered and plotted in a scatter plot. Since there were a variety of carburetor configurations and settings tested, the resultant data had more variability than the data set from the 40HP engine. Examples of the data from each method are shown in Figure 45 below. Other parameters, beside the emissions output, were considered in this step.

Examples include exhaust gas temperature, catalyst temperature, and running quality. These other parameters were also plotted against air/fuel ratio to understand the trends.



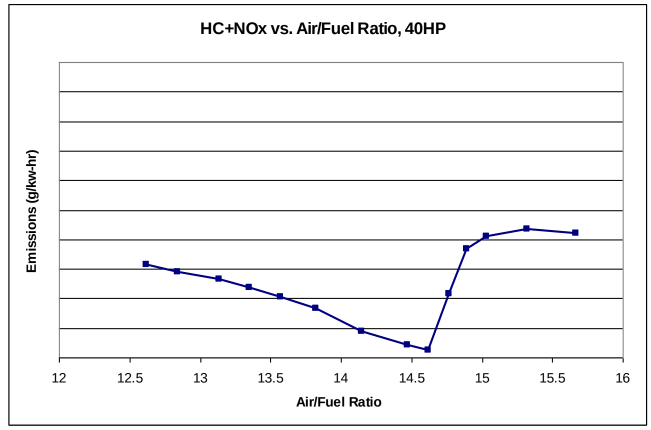


Figure 45: 6HP and 40HP Post-Catalyst HC+NOx Emissions vs. Air/Fuel Ratio

Since the emissions data for the 6HP and 20HP engines were collected utilizing various carburetor settings, there were some mode points that resulted in a more scattered data set. As a result, an empirical approximation was necessary to describe the data set. A simple model was used, which consisted of two line segments that intersected at the stoichiometric air/fuel ratio. The two line approach was necessary to describe the abrupt change in post-catalyst NOx emissions lean of stoichiometry at some of the mode points. The lines were intended to follow the upper bound of the scatter plot since the maximum emissions levels were the primary focus of this analysis. Figure 46 below shows an example plot of the linear approximation applied to the Mode 2 data set from the 6HP engine. Since the 40HP data were generated from a dedicated test, the data did not exhibit the same type of variability so no empirical model was necessary.

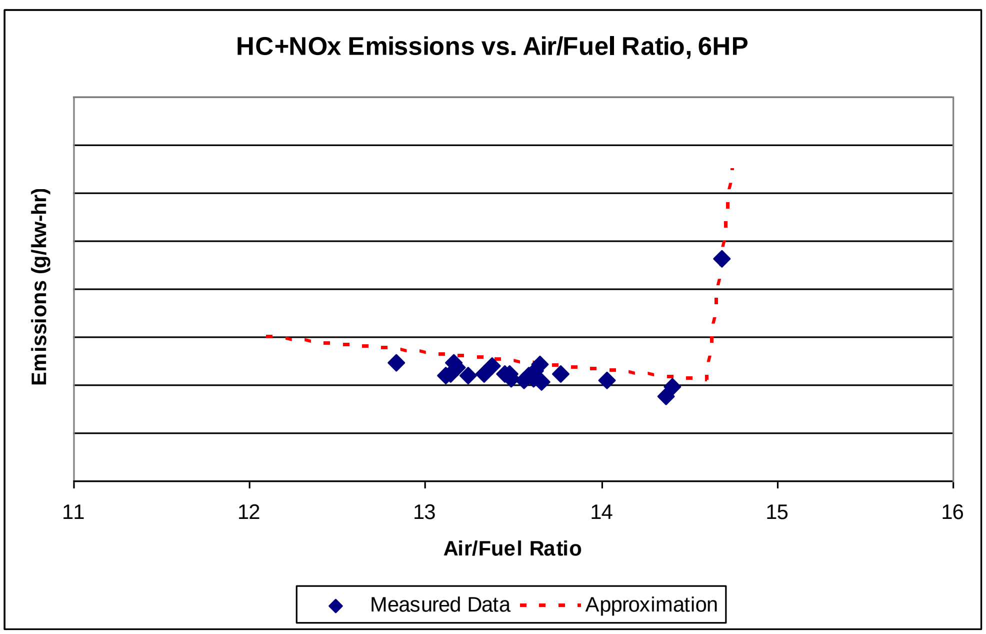


Figure 46: 6HP Empirical Model Applied to Post-Catalyst HC+NOx Emissions vs. Air/Fuel Ratio

At this point, the air/fuel ratio variability range and the trends of air/fuel ratio versus post-catalyst emissions were understood. The two pieces of information for each mode point were then combined. This is depicted graphically in Figure 47 using the 6HP Mode 2 data as an example. It should be noted that only the +/- 3 standard deviation ranges determined in the first step and not the average values of the current production engines were used for the analysis. When estimating the emissions, it was assumed that the nominal setpoint of the fuel system would be adjusted at each mode point to deliver the best overall emissions performance within the bounds of the physical engine limits. Graphically, this is represented by adjusting the position of the blue band (which represents the total size of the air/fuel ratio variability) to the left or right in Figure 47. The limits generally included exhaust gas temperature, catalyst temperature and torque output at the high load points, and running quality at the low load points. Shifting the nominal air/fuel ratio setpoints for each mode point individually is very feasible on the 40HP engine due to the EFI control system, but this method may not be a good assumption for the carbureted engines. The hardware changes made to change a single mode point typically affect more than just that mode point when calibrating a carburetor.

For example, with the data shown in Figure 47, it was assumed that the upper bound of the air/fuel ratio range should not be set to deliver air/fuel ratios leaner than stoichiometry. This was set in this manner to avoid the dramatic rise in post-catalyst NOx, as shown as the data point to the far right in Figure 47. In cases such as the one shown in the example below where the air/fuel ratio range exceeded the range of the available data, a simple linear extrapolation was assumed to estimate the emissions output on the periphery of the air/fuel ratio range.

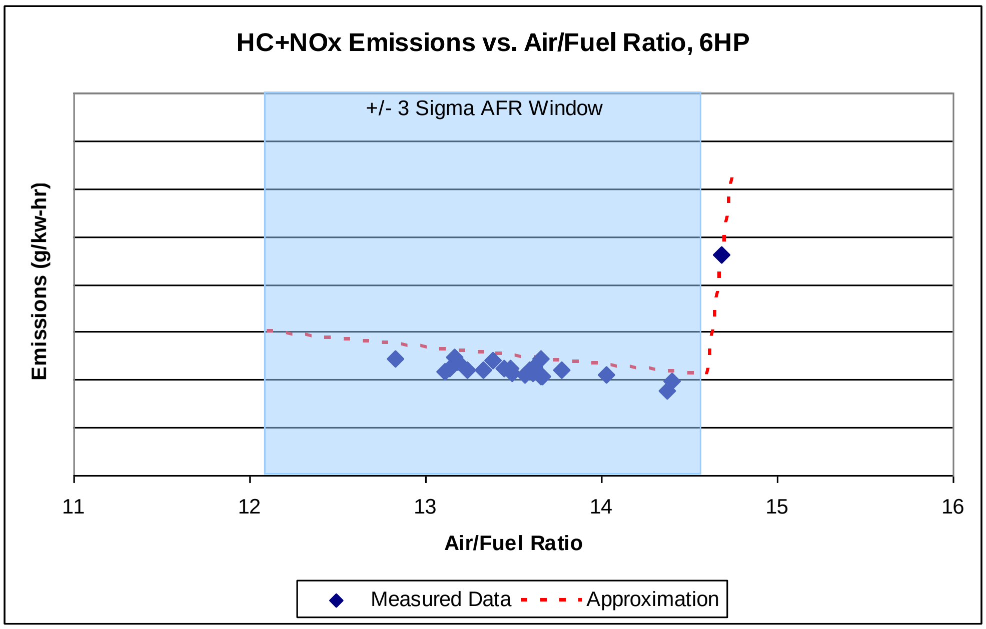


Figure 47: 6HP Air/Fuel Ratio Range Estimation Applied to Post-Catalyst HC+NOx Emissions Data

Once the estimates for the minimum and maximum HC+NOx emissions were determined at each mode point for each engine family, the results were added to calculate the total 5 mode values. These results were compared with the +/- 3 sigma range of current production, non-catalyst versions of each engine family. The results are shown in Figure 48 below. These data suggested that the highest emitting catalyst 6HP and 20HP engines could have higher HC+NOx emissions than the lowest emitting non-catalyst engines. This does not mean that adding a catalyst to a particular engine would make the emissions go up, however. The hydrocarbon emissions were the primary driver for this phenomenon since the contribution of HC to the total HC+NOx value was much higher than the contribution of NOx. A catalyst engine that has a rich fuel system would have relatively low HC conversion. A non-catalyst engine that operates with optimal air/fuel ratio at the mode points could have lower engine-out HC+NOx emissions than the post-catalyst HC+NOx emissions from a rich operating catalyst engine.

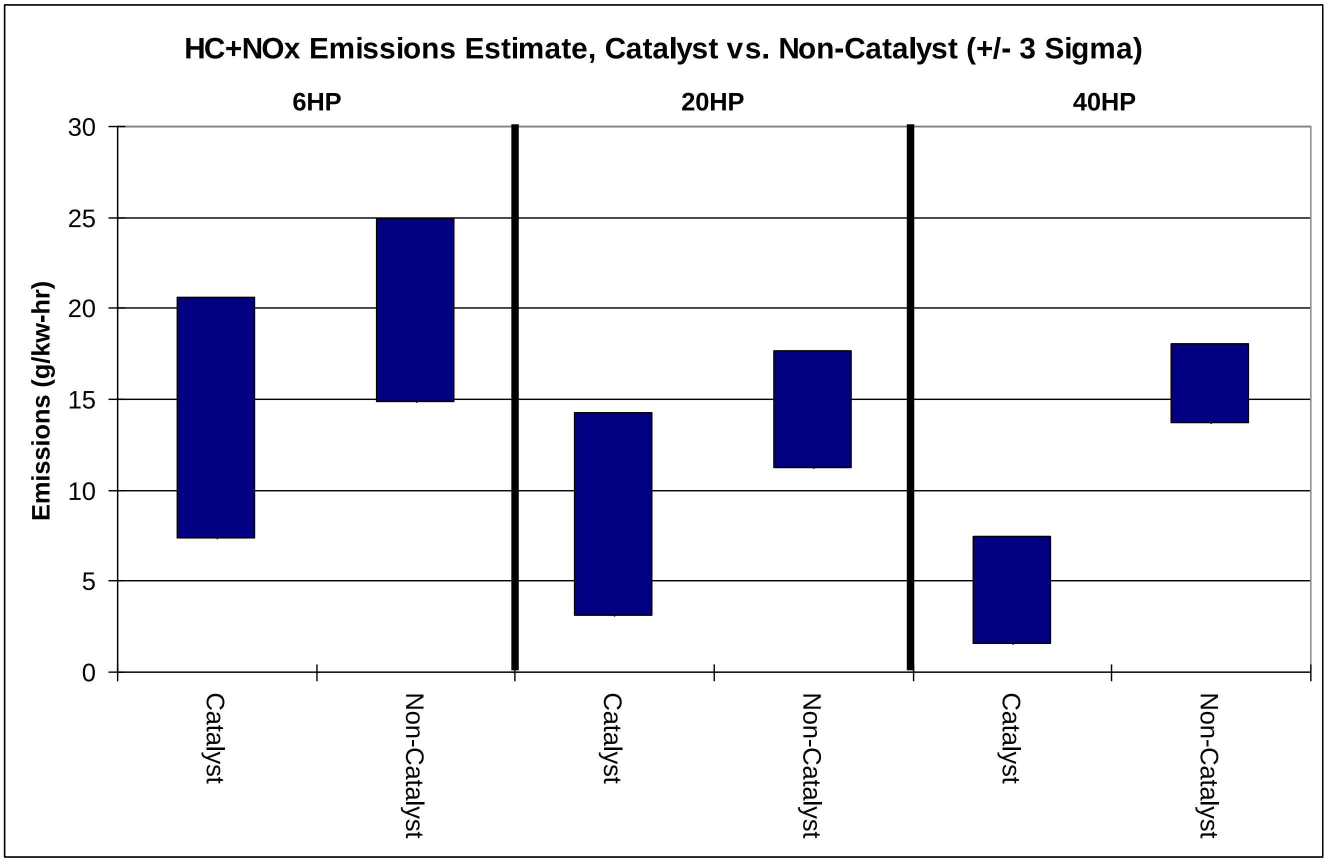


Figure 48: Catalyst vs. Non-Catalyst HC+NOx Comparison – 5 Mode Total HC+NOx, +/- 3 Sigma Range

There were several limitations of the methodology used in this estimation. The values shown in Figure 48 do not include emissions deterioration values. The deterioration effects would include engine-out changes in emissions, catalyst conversion efficiency reductions due to degradation or poisoning (which could also affect the relationship between conversion efficiency and air/fuel ratio). Also, the emissions output relationship to air/fuel ratio was determined by a single engine from each family. There will be engine-to-engine variability of emissions at a given air/fuel ratio. If the nominal setpoints of the carburetors are biased leaner than the current production engines, there may be increased air/fuel ratio variability (the carburetors may get more sensitive to manufacturing tolerances due to the small passages associated with lean settings). All of the previous aspects would tend to under-predict the emissions variability. One aspect of the methodology used that may over-predict the emissions range was the assumption that the worst-case engines would operate at the 3 sigma rich limit at every mode point.

Summary of Results and Conclusions – Small Outboard Design and Development

The small outboard piece of this project began by selecting and evaluating the current production versions of three engine families below 50HP. The initial evaluation consisted of understanding the non-catalyst emissions levels, power output (including the effect of increasing exhaust backpressure), oil consumption and water intrusion characteristics. These results established the baseline performance and served as the inputs into the design process of the catalyst versions.

Since three engine families were developed, a variety of solutions were implemented. The first step in the design process involved selecting the catalyst type and size. Both ceramic and metallic catalyst elements were chosen to include in the prototype designs. The exhaust system concepts were laid out and refined using computer aided analytical tools to optimize the flow and catalyst utilization. Some analysis of the cooling system was also performed. Once completed, the design process yielded three unique solutions that fit within the constraints of the prototyping methods available for this project, yet simulated the constraints of manufacturing processes that would likely be used in production.

After the design process was complete, prototype catalyst engines were constructed. Existing, current production engines were used as the basis for the prototypes. The stock parts were machined as necessary to accept the prototype pieces used to house the catalyst. The prototype pieces were made from machined billet aluminum, prototype investment castings, and other methods. The modifications necessary to mitigate any water intrusion issues identified were also included at this time. In addition, the engines were weighed and the weight increase over the current production design was calculated. The 20HP engine weight increase caused the total weight to cross the limit of what could be considered a "portable" engine. Four engines of each family were constructed and were scheduled for different testing tasks.

Once engines were built, they were tested on the dynamometers. The cooling system was evaluated to assure that the prototype hardware would not be compromised due to the additional thermal loading from the catalyst. In addition, the water condensation in the exhaust was evaluated. The multi-cylinder engines needed modifications to their cooling systems to control the metal temperatures, thermostat cycling, and water condensation in the exhaust. Once the cooling system configurations were stabilized, the emissions output and engine performance were measured. The fuel systems were calibrated to deliver the best combination of emissions reduction, running quality, power, hardware integrity, and driveability.

Once all the necessary changes were made to the configuration of the engines based on the dynamometer testing, one engine from each family was endurance tested in a tank. The tank endurance test was performed at full power for 100 hours. The goal of the tank endurance test was to ensure that the prototype hardware had adequate durability (appropriate for a research project, not fully qualified) prior to running the boat endurance test. The boat endurance tests were the final tests to be completed. The boat endurance test was performed using a customer duty cycle intended to simulate the ICOMIA duty cycle. Emissions tests were conducted before, in the middle of, and after the boat endurance test in order to understand the emissions deterioration. The results were mixed due to the influence of air fuel ratio. It was difficult to separate out the individual contributions of engine-out emissions degradation, catalyst deterioration, and air/fuel ratio change effects. The air/fuel ratio changes had the largest influence on the final emissions output.

Due to the pronounced sensitivity to air/fuel ratio, an estimate of emissions output as a function of air/fuel ratio was calculated. This estimate was focused on the effects of air/fuel ratio, so catalyst deterioration was not included. Using the statistical range of air/fuel ratio measured on previous emissions audits and data relating the air/fuel ratio to post-catalyst emissions from the prototype engines, the overall post-catalyst HC+NOx emissions results were estimated. An estimate for CO was not provided because the expectation is that on very rich fueled engines, the CO conversion would be near zero, so the total CO would not be appreciably different between a catalyst and a non-catalyst engine.

Overall Project Summary

Final Project Summary

Overall, the test program was very successful and met the goals for the project. Prototype engines of one family of large outboards and three families of small outboards were constructed and successfully tested. The main test was comprised of 350 hours of boat endurance testing accompanied by emissions tests at the start, middle, and end of endurance to determine emissions deterioration. Emissions reductions observed on the engine families met expectations.

The large outboard endurance testing successfully ran two engines through customer cycle boat endurance to determine the catalyst deterioration. Both engines maintained emissions levels below the 5.0 g/kw-hr HC+NOx target value. Despite using an increased ceramic catalyst mount mat density compared to the catalyst design from the original project, the catalyst element slid partially out of the mantle on one engine. Efforts to positively retain the catalyst with the "stop ring" proved ineffective at containing the catalyst.

The work done in this project demonstrated the use of catalytic converters in small outboard engines with open loop fuel system operation. A variety of catalyst mounting and exhaust system layouts were developed and were shown to be reliable during boat endurance testing. Both ceramic and metallic catalysts were used successfully in testing. The designs of the catalyst versions of the engine families focused on approaches to solutions that would simulate production-like designs. All three engine families required design changes to minimize water intrusion into the catalyst.

The emissions output and catalyst deterioration results after endurance testing completed were mixed. The catalysts reduced the HC+NOx emissions output, but the amount of emissions reduction was heavily influenced by the air/fuel ratio control of the fuel system. Based on the known air/fuel ratio variability of current production engines coupled with the understanding of the post-catalyst emissions reduction as a function of air/fuel ratio using the prototype engines, an estimate of the overall emissions variability was determined. The analysis showed that the smaller engines had lower emissions reduction potential due to the fuel system variability. The CO emissions measured were within expected ranges. Little or no CO conversion occurred due to the low conversion efficiency under rich operating conditions. It is expected that the upper range of CO emissions will not be substantially different comparing catalyst and non-catalyst engines with open loop fuel system operation. The amount of air/fuel ratio variability demonstrated on the small engines in this project is likely representative of other small outboard engines from the rest of the industry. Despite the air/fuel ratio variability, the engines developed in this project reduced the amount of HC+NOx exhausted as compared to the current production non-catalyst engines.

In order to demonstrate low emissions output, the open loop fuel system engines were finely calibrated to run relatively lean (essentially just slightly rich of stoichiometry at most mode points). However, there were recorded incidents of engine stalling during the customer cycle boat endurance test due to the relatively lean operation. These lean settings degraded the engine running quality/robustness and made the carburetors more prone to contamination. Production programs intended to develop open loop fuel system catalyst engines would benefit greatly by investigating methods to reduce air/fuel ratio control variability. This is especially true of the carbureted engines. The air/fuel ratio control was the single largest influence on emissions output.

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Appendix

Overview of Marine Outboard Construction